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EVALUATION OF MULTIPARAMETER EDDY CURRENT TECHNOLOGY FOR INSPECTION OF STEAM GENERATOR TUBING

S.D. Brown
Battelle
Columbus Laboratories

Date Published — March 1981

PREPARED FOR THE CORROSION SCIENCE GROUP
DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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EVALUATION OF MULTIPARAMETER EDDY CURRENT TECHNOLOGY FOR INSPECTION OF STEAM GENERATOR TUBING

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FOREWORD

Since 1975, Battelle-Columbus Laboratories has been performing an evaluation of the eddy current method for detecting defects in steam generator tubing, under subcontract from Brookhaven National Laboratory. This work has been funded by the Nuclear Regulatory Commission's Office of Standards development and has been designed to provide assistance to that office in developing criteria for inservice inspection of nuclear steam generator tubing and for determining the reliability of the inspection techniques currently in use. The following is the final report on this work.

The titles and authors of the previous reports are listed at the end of this foreword. The first of these reports, prepared in 1975-6, evaluated the reliability of the then standard single frequency eddy current method of inspection for a number of defects typical of those found in operating steam generators. The second report, prepared in 1977, evaluated the effects of denting in steam generator tubing on the ability of the eddy current technique to detect defects in the dented areas. The third report, prepared in 1979, described an evaluation of selected signal processing methods for detecting steam generator eddy current signals, primarily in areas where the signal from the defect otherwise would be masked by signals from tube support plates or dents.

In the last few years, there has been an increase in the commercial use of multi-frequency eddy current techniques for inspecting steam generator tubing. In the fourth phase of the Battelle program, therefore, emphasis has been placed on evaluating capabilities of some of the multi-parameter eddy current techniques currently in use for detection of defects in steam generator tubing, particularly where these defects are located inside tube-to-tube support plate or tube-to-tube sheet crevices.

It is clear from this work, that detection of a defect in a steam generator tube is difficult when the signal from the defect is in juxtaposition with signals from support plates, dents, or deposits on the outer

surface. The results presented in the following report will be of use to the Nuclear Regulatory Commission in their evaluations of the reliability of eddy current inspections that yield complex signals as described to them by the utilities. Further, they can serve as a basis for adoption of codes and standards for eddy current inspection using multi-parameter multi-frequency techniques. This report, however, describes the state-of-the-art as of the fall of 1979 and the winter of 1980; there continue to be new developments in eddy current inspection techniques designed for examination for specific types of defects, which both the NRC and the utility industry will have to continue to evaluate on a case by case basis. This report represents the completion of the Battelle-Columbus Laboratory program.
Mr. Steven D. Brown, who has been the Principal Investigator on all phases of this work, is presently with J.A. Jones Applied Research in Charlotte, North Carolina. Any questions of a technical nature should be directed to him at his new address. This work was funded by the U.S. Nuclear Regulatory Commission, Division of Engineering Standards.

John R. Weeks, Leader
Corrosion Science Group
Brookhaven National Laboratory

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FINAL REPORT

on

EVALUATION OF MULTIPARAMETER EDDY CURRENT TECHNOLOGY FOR INSPECTION OF STEAM GENERATOR TUBING

to

BROOKHAVEN NATIONAL LABORATORY
Upton, New York

March 7, 1980

by

Stephen D. Brown

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

EVALUATION OF MULTIPARAMETER EDDY CURRENT TECHNOLOGY FOR INSPECTION OF STEAM GENERATOR TUBING

by

Stephen D. Brown

SUMMARY

Multifrequency/multiparameter eddy current instrumentation for inspection of steam generator tubing has recently become commercially available. The instrumentation offers the steam generator owner a means to conduct parallel tests, i.e., normal tube integrity tests, sludge profiling and dent sizing in one pull through the tube. In addition, the real time suppression of extraneous variables such as support plates, denting and ID noise can be accomplished.

The Intercontrole IC3FA multiparameter instrument has been used for an assessment of multiparameter technology to detect and characterize defects in the presence of extraneous variables. A general mixing sequence has been developed which is applicable to both recirculating steam generators (RSG) and once-through steam generators (OTSG). Candidate mixing frequencies have been identified through the use of a computer program which models the IC3FA sequential mixing network.

Using appropriate models of defects at support plates and dented support plates, multiparameter technology has been found to offer advantages over single frequency approaches for more reliable defect detection and characterization.

INTRODUCTION

Background

Multifrequency/multiparameter eddy current instrumentation, for the in-service inspection of steam generator tubing, has recently become commercially available with the introduction of the Intercontrole IC3FA in 1977 and the Zetec MIZ-12 in 1979. With multifrequency eddy current, the test coil is

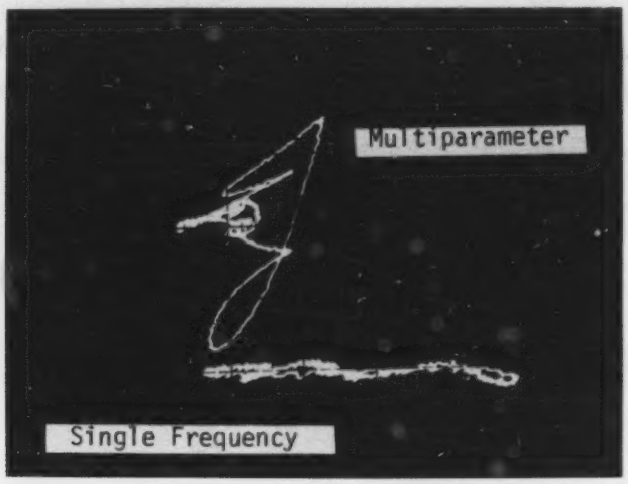
driven at more than one frequency; three in the case of the IC3FA and as many as four with the M1Z-12. Exciting the coil at multiple frequencies allows for the performance of parallel tests during one pull through the tube, i.e., normal tube integrity tests, dent sizing and sludge/debris profiling. This can result in a reduction of generator inspection time. Multiparameter eddy current approaches take a linear combination of inphase and quadrature signals of an extraneous variable, i.e., plate, dent or ID noise, at more than one frequency for the real-time suppression of the variable.

Approaches for characterizing defects in the presence of extraneous variables are necessary and have been in service for a number of years. Figure 1 illustrates signals from a dented support plate (RSG unit) which also has wastage occurring at the plate edge. At the normal inspection frequency of 400 KHz using a conventional differential coil, the dent signal masks the wastage signal precluding defect detection and characterization. The use of an alternate test coil, i.e., rotating pancake coil, provides for the accurate characterization of wastage occurring in proximity to a dented plate, but this inspection method is somewhat slow and tedious. Multiparameter eddy current offers an attractive alternative in that the dent can be suppressed in real time using conventional differential coils with no additional increase in inspection time. Figure 1 also shows results obtained using a multiparameter approach. The defect signal is clearly present with the result obtained at the normal differential probe pull speed.

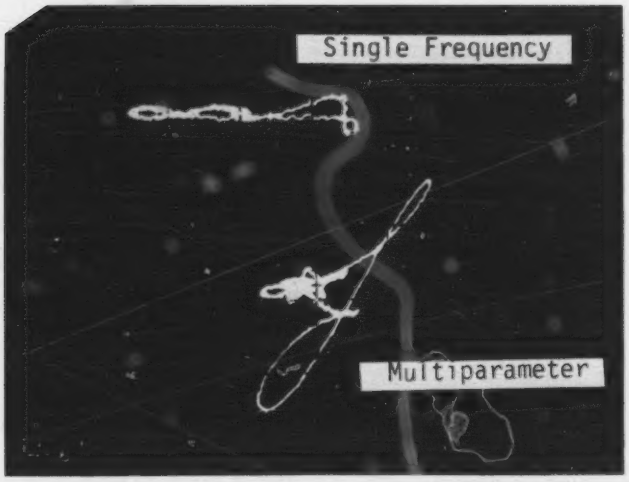
Analog/digital subtraction techniques are another method used for the characterization of defect signals at support plates or tube sheet. However, the occurrence of denting or the presence of tube ID noise precludes the reliable use of this method for accurate defect characterization.

Objective

The objective of this project was to assess commercially available multiparameter eddy current instrumentation with regards to its capability to characterize steam generator tubing defects in the presence of extraneous variables. Extraneous variables considered included support plates and dents. Specific tasks included (1) the development of optimal generic muitiparameter



Wastage Signal Masked by Dent



Wastage Signal Distorted by Dent

FIGURE 1. WASTAGE DETECTION/CHARACTERIZATION WITH MULTIPARAMETER EDDY CURRENT.

mixes, i.e., linear combinations of frequencies, applicable to both RSG and OTSG units, (2) estimation of mixing error, which is defined to be the error introduced in estimating the depth of a discontinuity, due to the residual which remains after an extraneous variable is suppressed and (3) assessment of the multiparameter eddy current method to accurately characterize simulated steam generator defects in the presence of an extraneous test variable.

MULTIFREQUENCY/MULTIPARAMETER INSTRUMENTATION

General Layout

The Intercontrole IC3FA is a multifrequency/multiparameter eddy current instrument with the capability to simultaneously excite an eddy current probe at three frequencies. The selected frequencies may assume any value from 5 KHz to approximately 750 KHz.

The IC3FA consists of a main frame and eight plug-in modules. Three of the plug-in modules are differential frequency modules identified as F1, F2 and F3; one plug-in is an absolute frequency module identified as FA; and one plug-in is called the display module. The remaining three plug-ins are mixing modules and are identified as C1, C2 and C3. A front panel illustration of the IC3FA and the module bin designation is shown in Figure 2.

It is normal practice to use the IC3FA with a standard differential probe coil, hence the three frequency modules F1, F2 and F3 are referred to as differential frequency modules. The absolute frequency module FA is coupled to the F3 module and hence is forced to operate at the F3 frequency. A psuedo-absolute signal is generated within the FA module and is useful for sludge profiling and the detection of gross wall thinning. The operating frequency of each frequency module F1, F2 and F3 is fixed and is determined by an oscillator/filter card which may be removed and replaced by one of a different value by the user.

The display module has front panel controls for pushbutton selection of coil supply current for each frequency module, selection of the display mode to an auxilliary storage scope and DC saturation current control for eddy

FREQUENCY MODULES MIXING MODULES

DISPLAY MODULE

F1 F2 F3 FA DM C1 C2 C3

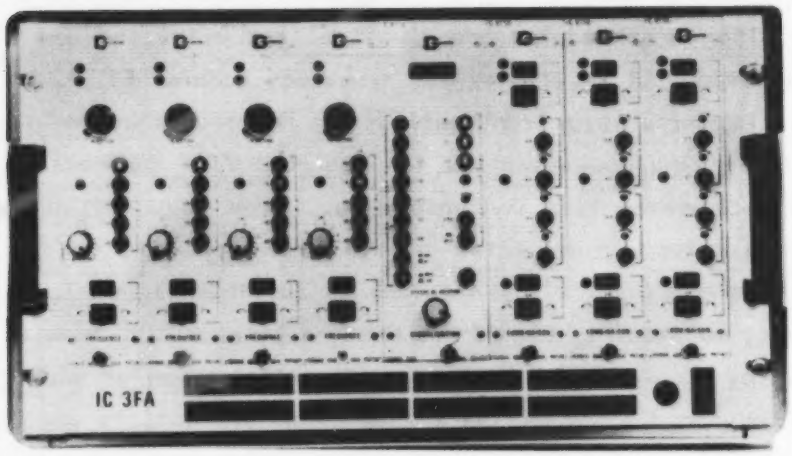


FIGURE 2. IC3FA FRONT VIEW.

current probes which contain an extra coil for magnetic saturation. This latter item is useful for tubes which exhibit magnetic permeability variations.

The mixing modules C1, C2 and C3 functionally act as a differential amplifier. The three modules are identical and allow the user to select as inputs, the outputs of any two of the frequency modules F1, F2 or F3, outputs of other mixing modules or combinations of the frequency modules and mixing modules. The mixing modules allow for the real-time suppression or subtraction of an extraneous test variable, i.e., tube support, ID noise or dent which may mask defect signal data.

Functionally, the IC3FA system is shown in Figure 3. Shown are the four frequency modules F1, F2, F3 and FA, the three mixing modules C1, C2, C3, and the display module. An X-Y storage scope (Zetec vector analyzer or equivalent) is used for display of the frequency module outputs and the inputs or outputs of the mixing modules.

Mixing Module Details

The differential frequency modules F1, F2 and F3 are each functionally similar to the conventional single frequency instrument EM-3300 used for steam generator inspection and hence are not discussed. The mixing modules C1, C2 and C3 represent a new concept for the inservice inspection of steam generator tubing and module specifics are now considered in more detail.

An IC3FA mixing module is illustrated in schematic form in Figure 4. The purpose of the mixing module is to take the inphase and quadrature components of two input signals A and B, modify one or both of two signals by scaling and rotating to make them look similar, i.e., congruent. The two adjusted signals are then fed to a differential amplifier where the resultant output signal will be minimal. The two input signals A and B are generally the extraneous variable to be eliminated at two different frequencies.

Signal shaping is accomplished using weighting resistors which attenuate independently the inphase and quadrature components of an eddy current signal. The phase rotator A shown in Figure 4 allows for the rotation of signal A onto signal B. The phase rotator AB allows for the establishment

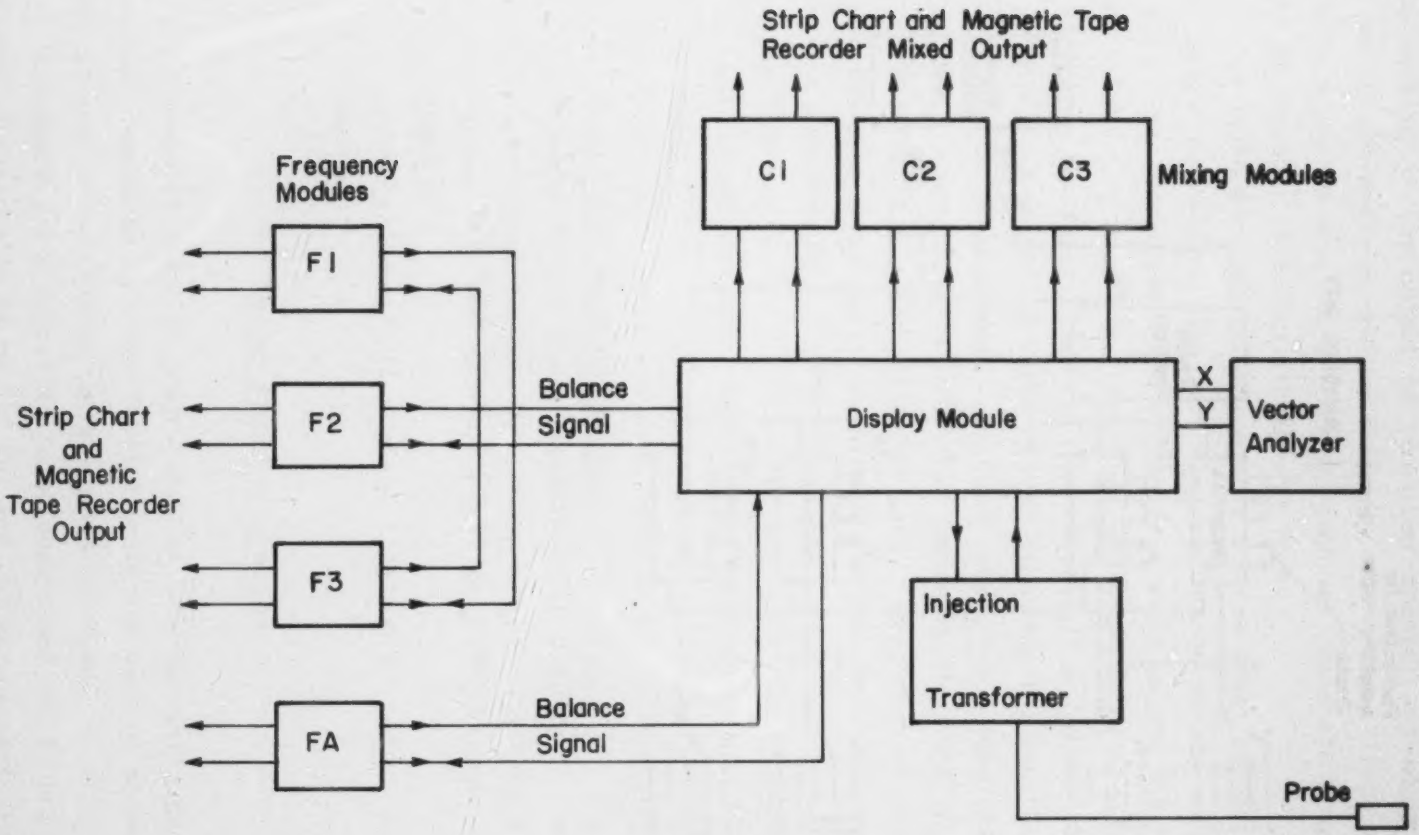


FIGURE 3. INTERCONTROLE IC3FA SCHEMATIC

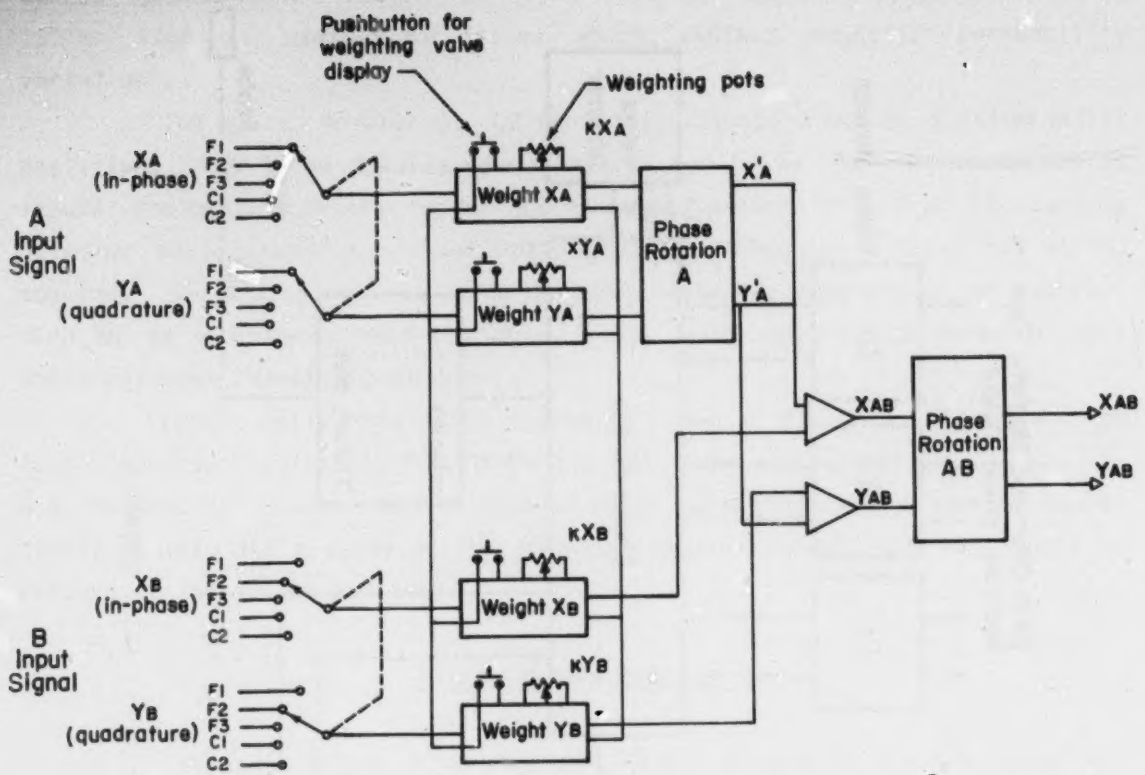


FIGURE 4. IC3FA MIXING MODULE SCHEMATIC

of phase setting at the output of the mixer channel and would normally be rotated as in conventional single frequency techniques, i.e., wobble horizontal with signal from a 100 percent through wall hole starting down and to the right as the coil is pulled through the hole.

The IC3FA display module contains a three digit LED for the readout of mixer weighting values. The weighting can assume values which vary from 000 to EEE. The normalized transfer function which exists for the weighting resistors is shown in Figure 5. The transfer function is linear and a value of EEE indicates the input signal is unattenuated, i.e., multiplicative scale factor of unity. A weighting value of 750 indicates the input signal amplitude is reduced to 50 percent of its input level, i.e., multiplication scale factor of 0.5. A weighting value of 500 indicates the input signal is completely attenuated, i.e., multiplier of zero. Weighting values from 000 to 499 assume the same scale factor relation as values from EEE to 500 with the addition of a sign change.

The front panel configuration for the IC3FA mixing module is shown in Figure 6. Control or indicator functions are as follows;

1. Phase A
   Controls and displays phase rotation of input signal A to mixer.
2. Mixer Input Weighting Factors
   Recessed screws above pushbutton LED display for selection of A signal input inphase (KX) and quadrature (KY) and B signal input inphase (KX) and quadrature (KY) weighting values.
3. Phase AB
   Controls and displays phase rotation of output signal AB from mixer.

Mixer Signal Progression

A somewhat detailed progression of eddy current signals through a mixer is now considered in order to illustrate the general sequence of events which occurs when an extraneous variable is suppressed.

A support plate signal is to be suppressed and F2 and F3 are chosen for purposes of discussion to be 400 KHz and 100 KHz respectively. F2 and F3

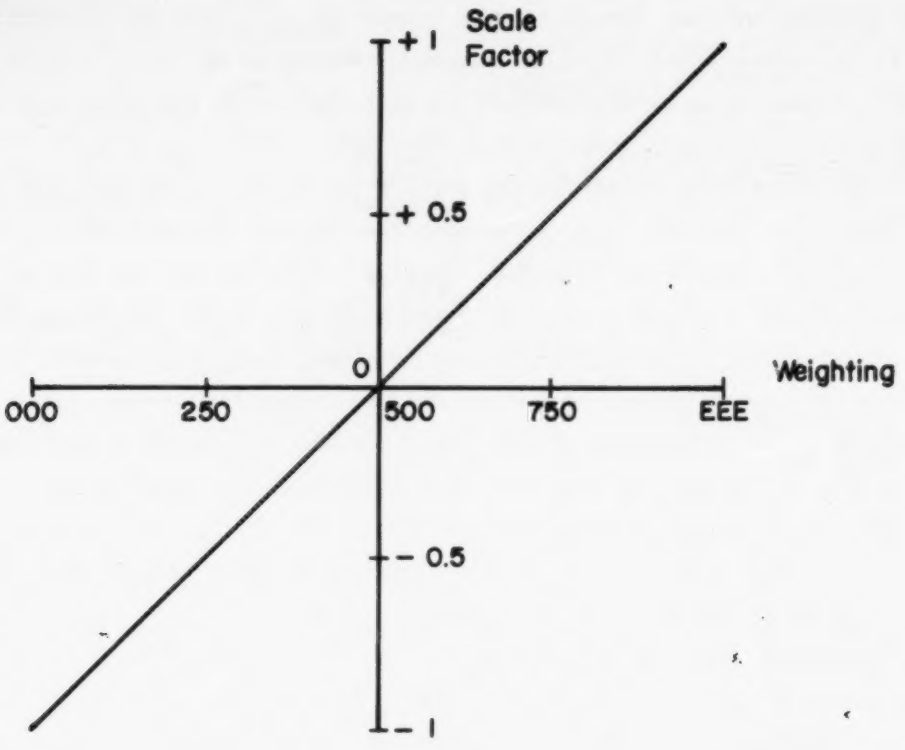


FIGURE 5. IC3FA MIXING MODULE WEIGHTING TRANSFER FUNCTION

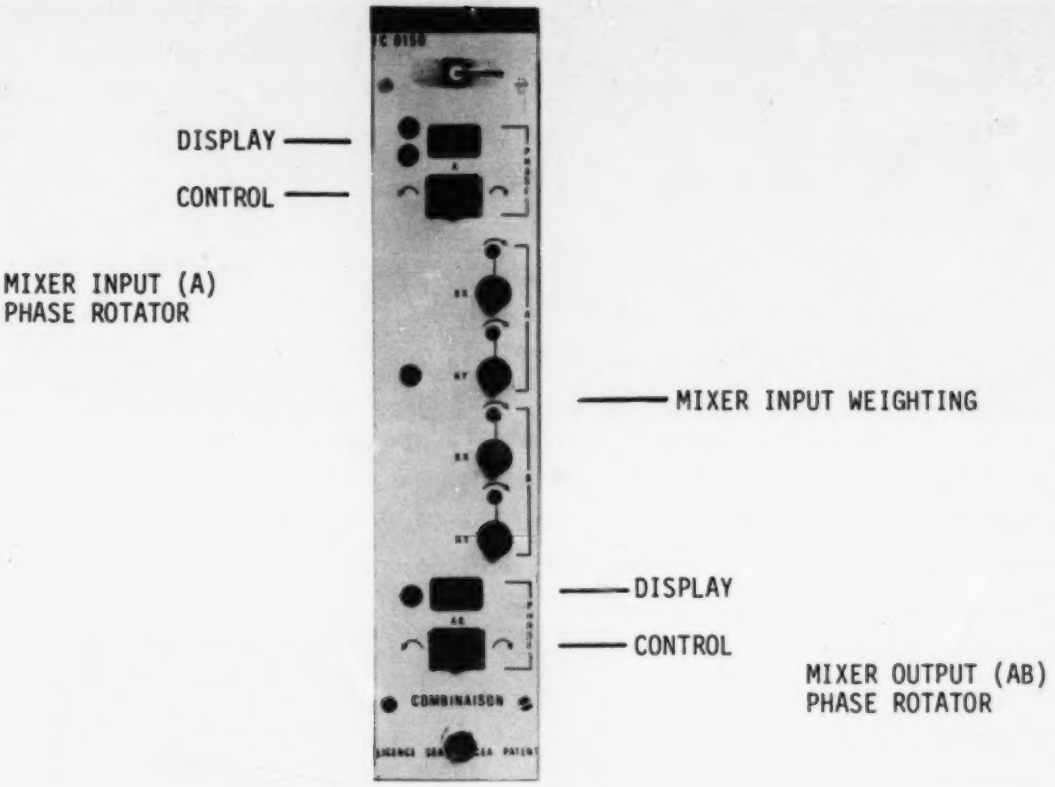
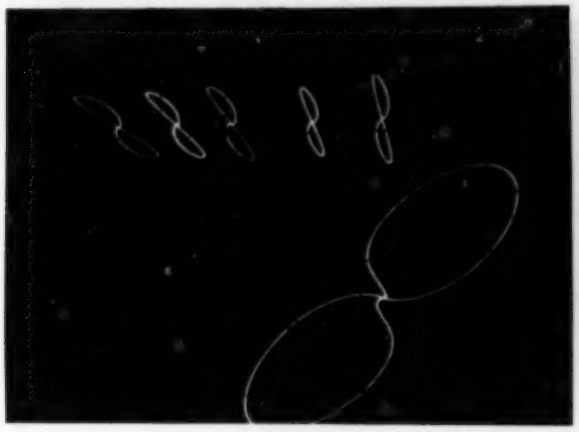


FIGURE 6. IC3FA MIXING MODULE FRONT PANEL.

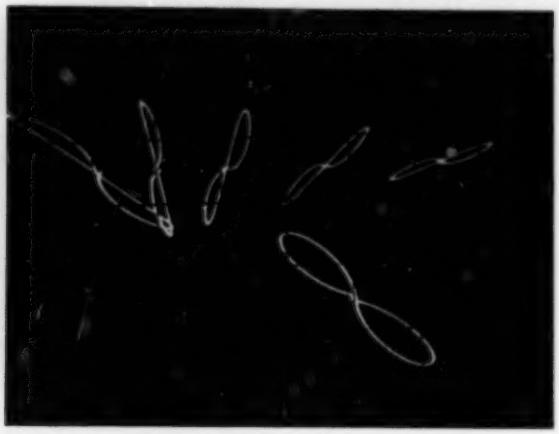
have been initialized at the frequency modules using conventional single frequency practices i.e., wobble horizontal. The C1 mixing module is selected and the C1 module A signal is chosen to be 100 KHz whereas the B signal is 400 KHz. The A and B signals at the input side of the C1 mixer are shown in Figure 7(a) and (b), where are illustrated a support plate and ASME Section XI defect standard signals at 100 KHz and 400 KHz. The two plate signals exhibit three characteristic differences: (1) they have different amplitudes, (2) different shapes, i.e., the 100 KHz plate signal has entrance and exit lobes which are somewhat rectangular in shape, and (3) they exhibit different orientations with respect to each other. A gain adjustment on the F3 frequency module will reduce the two plate signals to equal magnitudes as shown in Figure 7(c). Notice that the two plate signals still have different shapes. Rotation of the 100 KHz signal using the C1 mixing module A phase rotator places the two signals in synchronism, i.e., overlapping one another. Without using any weighting, the difference or residual between the 100 KHz and 400 KHz plate signals is shown in Figure 7(d). Use of appropriate weighting on the C1 mixer A channels, i.e., KX and KY, allows for the shaping of the 100 KHz plate signal so that it more closely resembles the 400 KHz plate signal. A weighted 100 KHz plate signal and residual is also shown in Figure 7(d). The two input plate signals are more congruent and the weighted residual is smaller than the unweighted residual.

The use of weighting affects all signals on either the mixer A or B channels. Of interest then is the shape of defect signals at the output of the mixer and the resultant phase angle curve which relates to the estimation of defect depth. What occurs can be seen by pulling the probe through the defect standard and looking at the input and output side of the mixer. For comparison, the initial 100 KHz and 400 KHz defect standard patterns are shown in Figure 7(a) and (b) respectively. Figure 8(a) shows the defect standard signals at the input side of the C1 mixer after gain reduction, rotation and weighting of the 100 KHz plate signal. The mixer output will be the dynamic subtraction of the 100 KHz and 400 KHz signals and is shown in Figure 8(b). The C1 phase rotator AB has been rotated so that the wobble is horizontal and the signal from the through wall hole starts down and to the right.



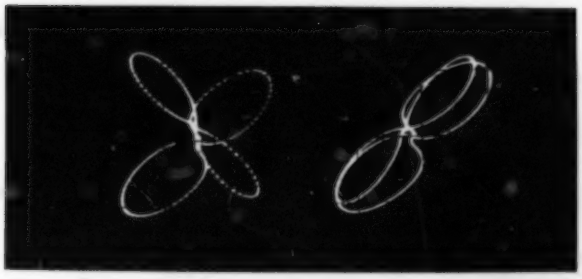
(a)

ASME STANDARD SIGNALS AND SUPPORT PLATE AT 400 KHz.



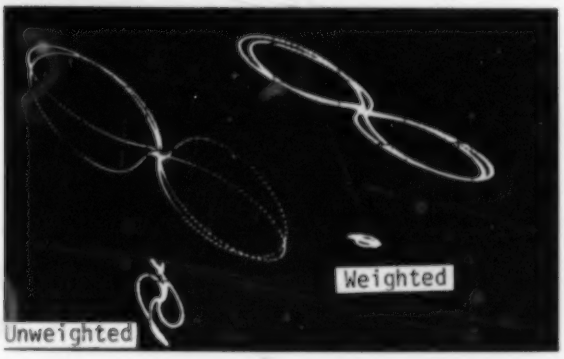
(b)

ASME STANDARD SIGNALS AND SUPPORT PLATE AT 100 KHz.



(c)

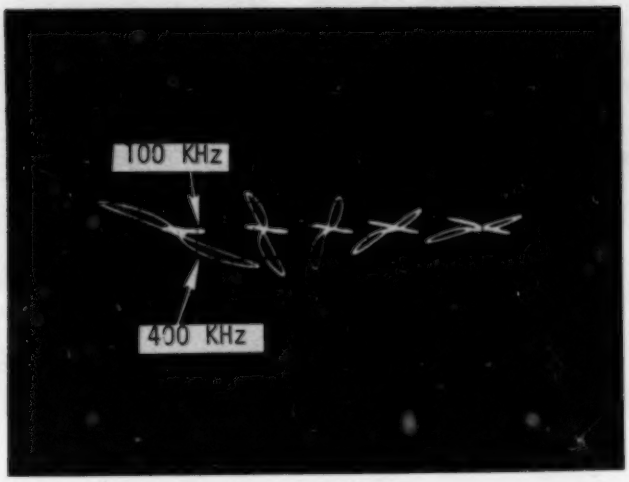
PLATE SIGNALS SCALED AND ROTATED



(d)

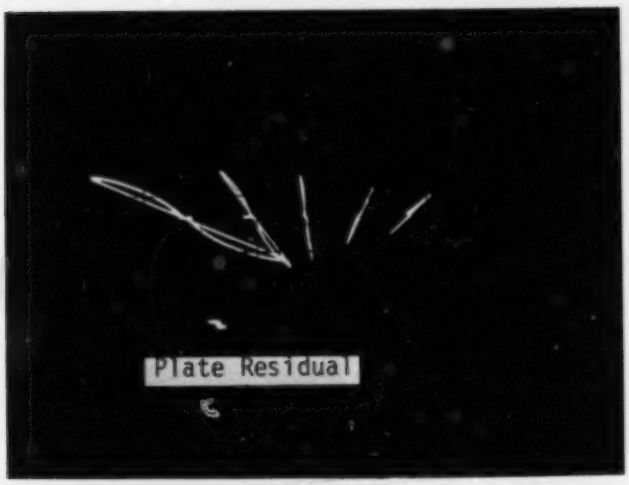
WEIGHTED AND UNWEIGHTED PLATE SIGNALS AND RESIDUALS

FIGURE 7. ILLUSTRATION OF PLATE SUPPRESSION.



(a)

100/400 KHz ASME STANDARD SIGNALS
AT INPUT SIDE OF MIXER



(b)

100/400 KHz ASME STANDARD SIGNALS
AT OUTPUT SIDE OF MIXER

FIGURE 8. DEFECT STANDARD MIXER
SIGNAL PROGRESSION

The resultant phase angle curve versus defect depth is shown in Figure 9 along with the conventional 400 KHz curve (0.050" wall tube). As is apparent, some minor phase compression has occurred but overall the 100 KHz/400 KHz mixed curve is similar to the basic 400 KHz except that it has been rotated counter clockwise, i.e., shifted to the left, relative to the 400 KHz curve. Figure 9 also illustrates the phase angle curve which is obtained using a 200 KHz/400 KHz frequency combination to perform the same plate suppression. The resultant phase compression is obvious. A general problem in mixing is the selection of frequencies F1, F2 and F3 which give the desired extraneous variable suppression while maintaining adequate phase spread in the output of the mixer.

EXPERIMENTAL APPROACH

Generic Mix Development

With single frequency eddy current, coil excitation frequency is the controlling factor which determines the amount of phase shift that is obtained for a given tube wall thickness. Phase shift is defined to be the difference in phase angle that is observed between the 100 percent and 20 percent through wall holes. The phase shift obtained with the multiparameter eddy current approach is a function of the frequencies which are combined and the manner in which they are weighted.

To simplify the development of a general mix configuration, the following generalization was made. In existing steam generator configurations, there are two general ranges of tube wall thickness encountered, i.e., 0.040"-0.042" and 0.048"-0.050". Once optimal mix frequencies F1, F2 and F3 were identified for the thicker wall tubing, these frequencies could simply be scaled upwards for the thinner wall tubing.

The three extraneous variables which are encountered in steam generator tubing inspection are the support plate/tube sheet, dent, and ID noise. The first two variables are the most important. In addition, tube ID noise is similar to a dent signal from an eddy current viewpoint in that it exhibits a comparable phase angle as referenced to the wobble axis. The magnitude of the

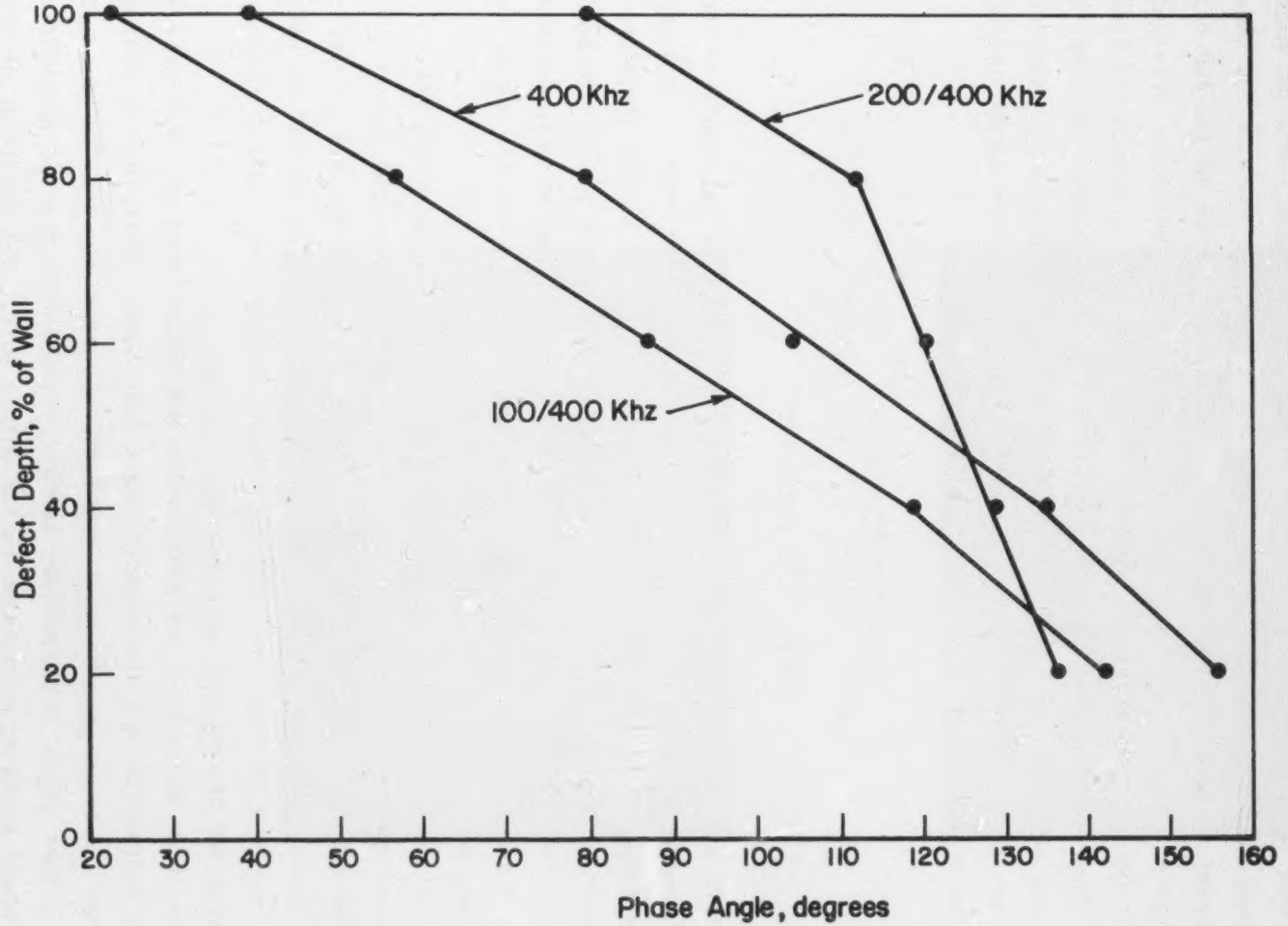


FIGURE 9. CALIBRATION CURVES FOR VARIOUS MULTIPARAMETER PLATE SUPPRESSION MIXES COMPARED WITH SINGLE FREQUENCY 400 KHz (0.050" wall tube).

ID noise signal is generally less than that of a dent although there are exceptions. Thus the goal is to configure a "mix", which is defined to be a series combination of frequencies and mixer outputs which provide for the suppression of a support plate and dent signals. Ideally, there is one general configuration applicable to all tube wall thickness ranges, with specific frequencies determined by wall thickness.

A general mix configuration does exist and in terms of the IC3FA modules is shown in Table 1(a). Three mixing modules C1, C2 and C3 are required in addition to the outputs of the three frequency modules F1, F2 and F3.

The plate is suppressed in C1 using frequencies F2 and F3, and in C2 using F1 and F2. A double mix or elimination of the plate is accomplished so that the C1 and C2 inputs to C3 are plate free. The dent is suppressed in C3 so that the output of C3 is plate free and dent free. In general, only one variable per mixer can be suppressed. For in-service cases where nondented support plates are encountered, the output of C1 or C2 could be used for the detection and characterization of plate-associated tube defects. For dented plates or for tubes containing ID noise, the output of the C3 mixer would be used for analysis.

Sequencing of plate/dent signals through the previously mentioned mix configuration is shown in Figure 10. Figure 10(a) shows the C1 mixer plate and dent signal inputs. The plate signals have been weighted and rotated using the C1 mixer Phase A rotator so that the C1 mixer plate output is minimal. Also shown in Figure 10(a) are the C1 dent signal inputs. Notice that the C1 output for a dent signal input is a dent. The same events occur in the C2 mixer where plate/dent inputs and outputs are shown in Figure 10(b). C3 mixer inputs/outputs are shown in Figure 10(c). Plate residual inputs/outputs and dent signal input and output residual are shown. Summarizing the logic behind this particular mix configuration, one variable per mixer is eliminated. For N variables, (N + 1) mixers are required. In our case there are two variables of interest, i.e., the plate and dent signal. A double mix is performed on the plate signal using the C1 and C2 mixers. The plate free outputs of C1 and C2 are then combined in C3 for the final suppression of the dent.

The mixing sequence has been defined in terms of general frequencies F1, F2 and F3. To identify optimal specific frequency selections, the matrix

TABLE 1

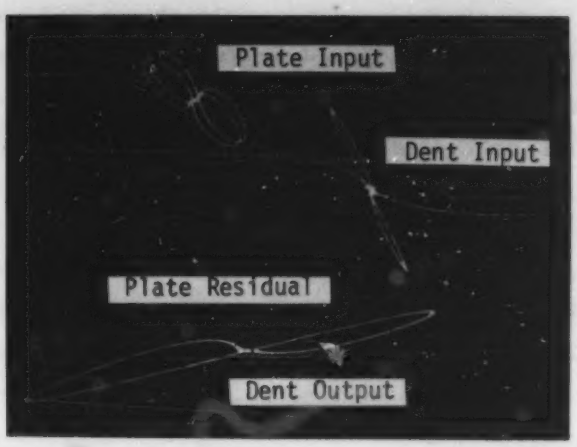
MIXING MODULE

	C1		C2		C3	
	A Input	B Input	A Input	B Input	A Input	B Input
Input to Mixer	F3	F2	F1	F2	C1	C2
Variable Suppressed	Plate		Plate		Dent	

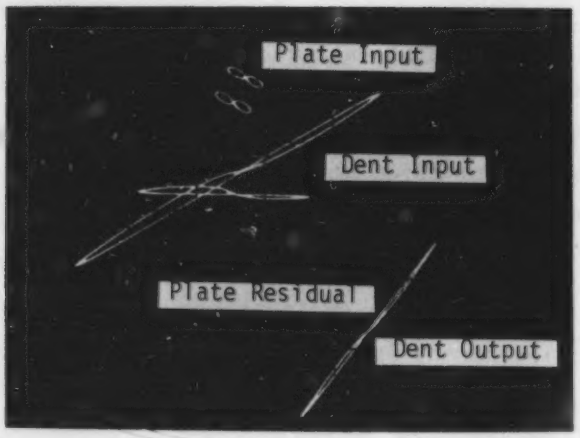
(a)

MIXING FREQUENCY (F3) \ BASIS FREQUENCY (F2)	100	200	300	400	500	600	700	800
100	--	x	x	x	x	x	x	x
200		--	x	x	x	x	x	x
300			--	x	x	x	x	x
400				--	x	x	x	x
500					--	x	x	x
600						--	x	x
700							--	x
800								--

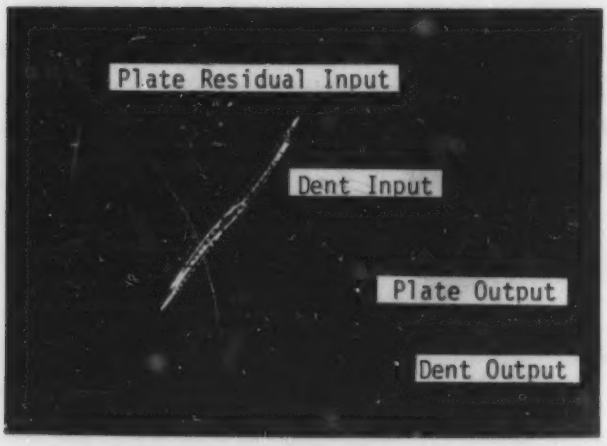
(b)



(a)
C1 MIXER DENT/PLATE INPUT/OUTPUT



(b)
C2 MIXER DENT/PLATE INPUT/OUTPUT



(c)
C3 MIXER DENT/PLATE INPUT/OUTPUT

FIGURE 10. DENT/SUPPORT PLATE PROGRESSION THROUGH C1/C2/C3 MIXERS

in Table 1(b) was constructed and combinations of mixing frequency (F3) and basis frequency (F2) were examined using a computer program for plate suppression. The matrix is symmetrical about the diagonal, hence only the top half needs to be considered since it makes no difference which is called a mixing frequency or basis frequency, i.e., F2 and F3 are interchangeable. In multiparameter eddy current, the extraneous variable being suppressed must be sampled at two different frequencies, hence frequencies lying along the diagonal are prohibited. Thus those frequencies identified by an x in Table 1(b) were considered in combination. Once optimal (F2/F3) combinations were identified for plate suppression, the (F2/F3) resultant was combined with a range of F1 values for selection of dent suppression frequencies. Thus it was anticipated that two sets of frequencies would result: F1, F2 and F3 for the 0.048-0.050" wall tube and F1', F2', F3' for the 0.040"-0.042" wall tube.

Mixing Error

With multiparameter eddy current, an extraneous variable is suppressed with suppression never perfect, i.e., a residual signal always remains. The residual can still influence a defect signal and result in some inaccuracy in estimating the defect depth. The difference between the actual defect depth and depth estimate obtained from interpreting the defect plus residual signal is the mixing error. An optimal multiparameter mix could be defined as one which minimizes the error in estimating defect depth. Optimal mixes are not necessarily those which have minimal residual since the phase spread of the mixed output channel is an important consideration.

The mixing error in general will be a function of the amplitude of the defect signal, the location of the defect with respect to the extraneous variable, and the extraneous variable residual. In the evaluation of optimal plate mixes, two series of standards were used. For the Westinghouse 0.050" wall tubing, flat-bottom holes were used at depths of 20 percent, 40 percent, and 60 percent through wall. At each depth, one, two, three and four holes were drilled at ninety degree intervals around the tube for controlling signal amplitude. The hole diameters for each depth corresponded to the ASME Section XI standard which is 3/16 in., for the 20 percent and 40 percent, and 7/64 in.

for the 60 percent. Each series of holes was then stepped through the support plate at an eighth-inch interval starting with the hole centered within the plate. See Figure 11(a). At each position, a probe was pulled through the defect and the output of the IC3FA C1 mixed channel was photographed from a storage scope. The resultant eddy current signal pattern was interpreted, assigned a phase angle and its depth estimated using a curve derived from the same hole free of the extraneous variable.

For the Babcock and Wilcox 0.040" wall tube, a similar approach was used except that a #60 FBH (0.040" diameter) was used. Anywhere from one to four holes at 90° intervals were initially placed a quarter of an inch inside the broached support plate and incremented at one-sixteenth inch intervals through the plate edge assuming a final position one quarter of an inch beyond the plate edge.

Defect detection/characterization in denting was examined using the Combustion Engineering 0.048" wall tube. Dent sizes ranging from 2 mils to 8 mils radial were used with ASME Section XI single flat-bottom holes at depths of 40 percent and 60 percent placed at the plate/dent edge and in the center of the dent. See Figure 12.

Simulated Steam Generator Tube Defects

Subsequent to the selection of optimal mixes, which were those combinations of frequencies which in general minimized the mixing error, artifical tubing defects were scanned. The particular defect type, shape and its location to the extraneous test variable was based on actual steam generator in-service inspection experience. Examples of simulated OTSG and RSG defect types and geometries are shown in Figures 13 and 14 respectively.

RESULTS

Mixer Analysis/Mix Development

The IC3FA C1, C2, C3 mixer sequencing can be modelled exactly using a series coupling of the equation which governs each of the respective mixers.

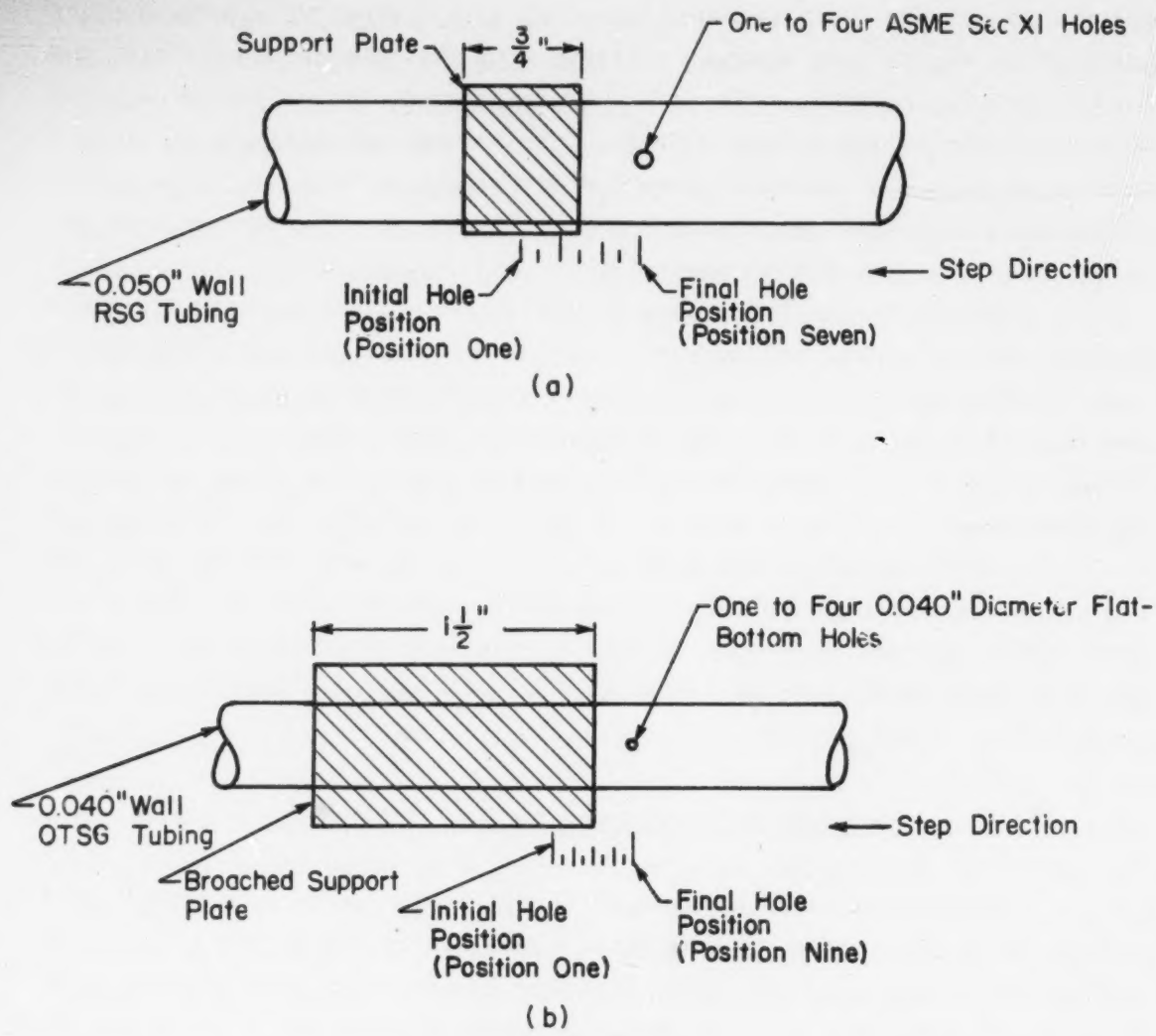


FIGURE 11. SUPPORT PLATE LOCATIONS USED FOR EVALUATING MIXING ERROR

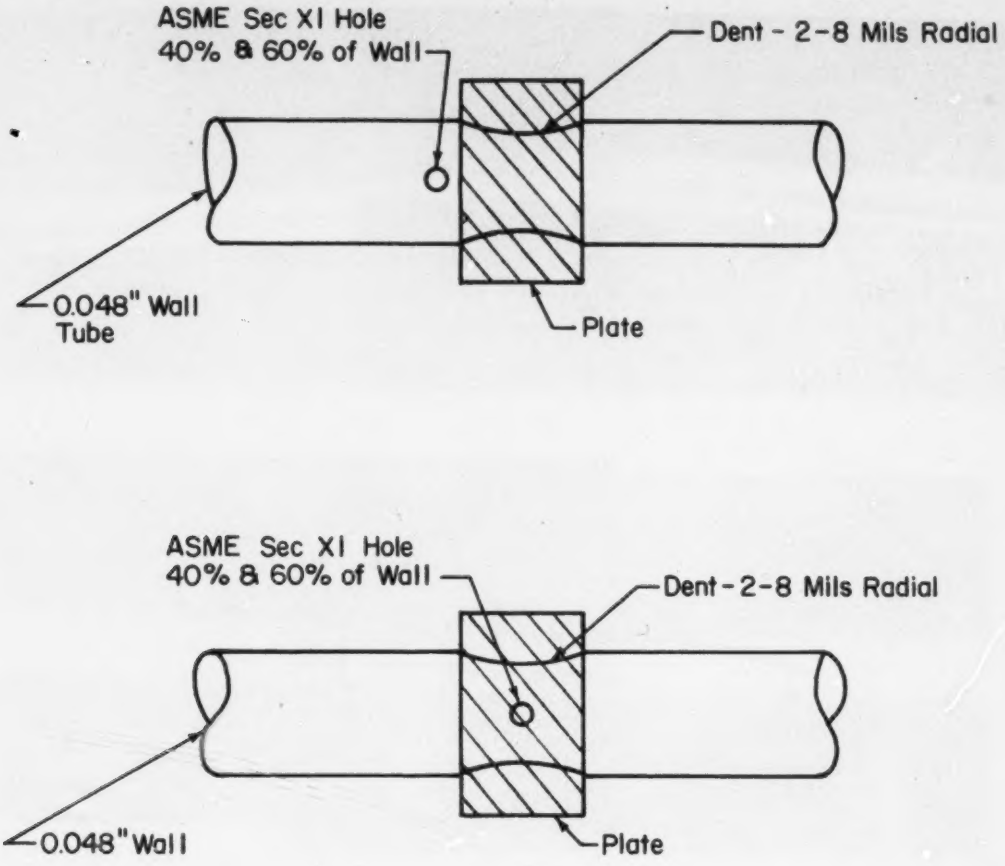
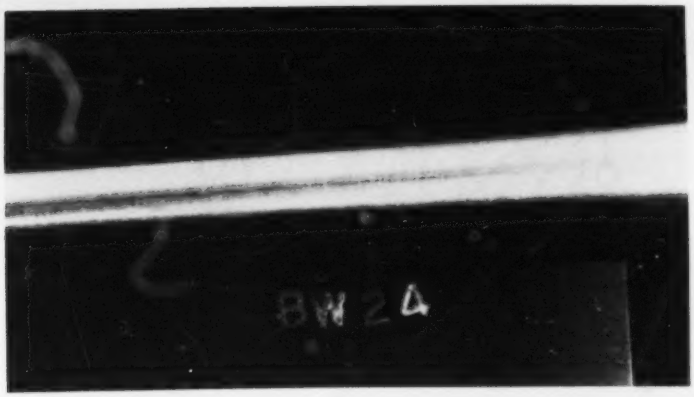
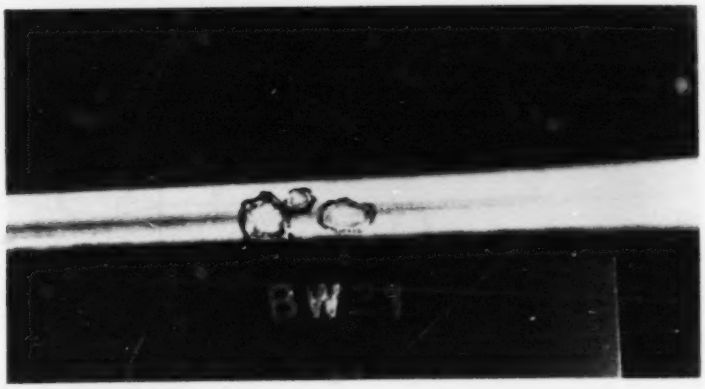


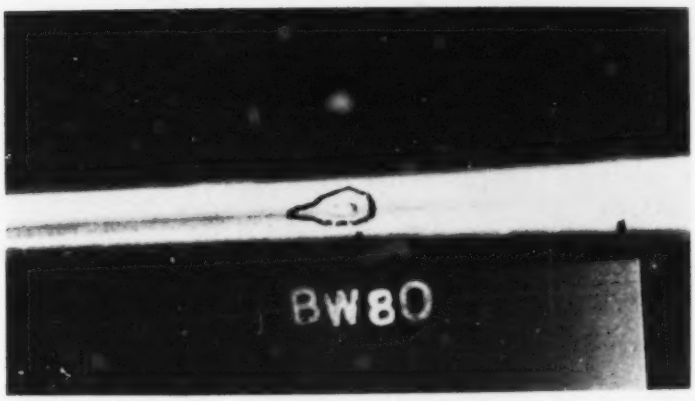
FIGURE 12. DENT SPECIMEN CONFIGURATION FOR DENT MIX EVALUATION



FRETTING



MULTIPLE SCALLOPING

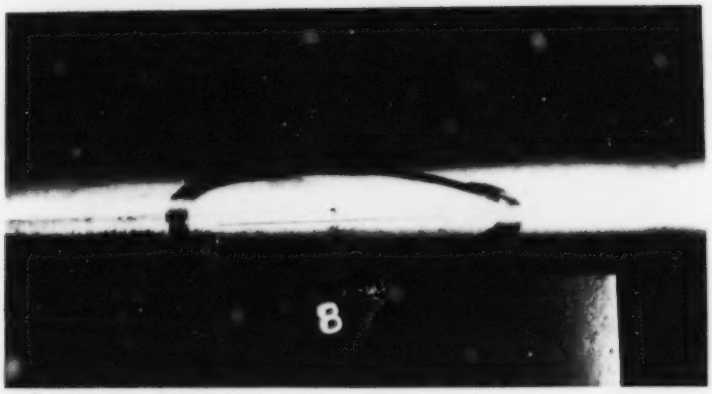


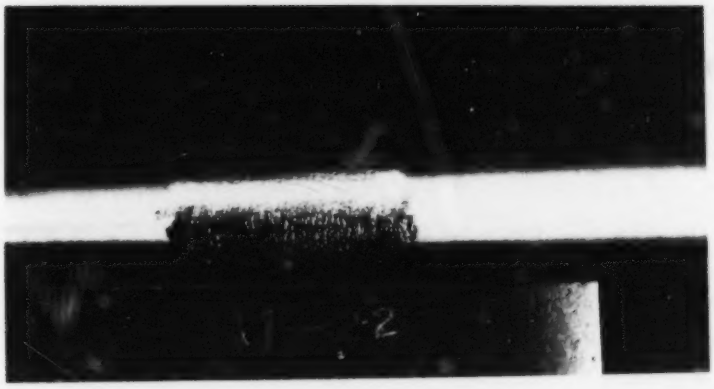
EROSION/CORROSION (TEARDROP)

FIGURE 13. SIMULATED OTSG DEFECTS

PITTING

AXIAL CRACK





WASTAGE

FIGURE 14. SIMULATED RSG DEFECTS

Figure 4, which illustrates the mixing module, can be used to write the mixer output in vector form as

$$\vec{A}-\vec{B} = (X'_a - K_3 x_b)\hat{i} + (y'_a - K_4 y_b)\hat{j} \quad . \tag{1}$$

The primed coordinates represent the output of the A phase rotator which operates on the input (x_a,y_a) after weighting. In terms of the A input signal we have

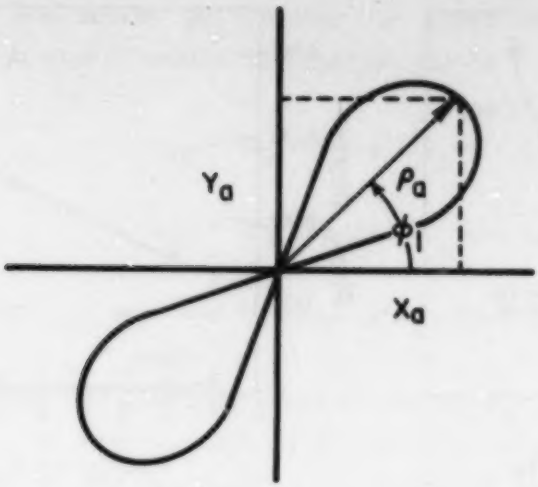
$$\begin{aligned} x'_a &= K_1 x_a \cos \Delta\phi - K_2 y_a \sin \Delta\phi \\ y'_a &= K_1 x_a \sin \Delta\phi + K_2 y_a \cos \Delta\phi \end{aligned} \tag{2}$$

where $\Delta\phi$ is the angle which $\vec{A}$ has to be rotated to lie on $\vec{B}$. Thus, the mixer output can be rewritten in terms of initial input components as

$$\begin{aligned} \vec{A}-\vec{B} = &\left\{(K_1 x_a \cos \Delta\phi + K_2 y_a \sin \Delta\phi) - K_3 x_b\right\}\hat{i} + \\ &\left\{(K_1 x_a \cos \Delta\phi - K_2 y_a \sin \Delta\phi) - K_4 y_b\right\}\hat{j} \end{aligned} \tag{3}$$

where the K_i are the mixer weighting coefficients, (x_a,y_a) and (x_b,y_b) are the A and B input signal components, and $\Delta\phi$ is the angle between the A and B samples of the extraneous variable. For a support plate signal, the above signal components are illustrated in Figure 15. Comparable signal components can be constructed for defects and dents.

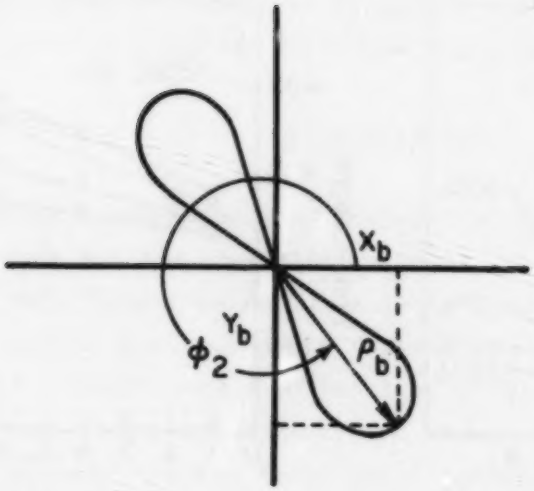
The magnitude and phase of the plate, defect and dent signals are frequency dependent. Figure 16 illustrates this dependency for 0.050" wall tubing where the magnitude data has all been normalized to a 1 volt plate signal. A simplification to Equation (3) can be accomplished by recognizing that in the C1 and C2 mixers for plate suppression, the A and B input signals are being scaled and rotated for equal and overlapping plate signals. Here, the detailed shaping which occurs is ignored by making all K_i equal to unity. The same approximation holds for the C3 mixer where the input signals (C1 and



A Signal
100 Khz

$X_a = \rho_a \cos \phi$

$Y_a = \rho_a \sin \phi$



B Signal
400 Khz

$X_b = \rho_b \cos \phi_2$

$Y_b = \rho_b \sin \phi_2$

$\Delta\phi = \phi_2 - \phi_1$

FIGURE 15. SUPPORT PLATE SIGNALS REPRESENTED AS DYNAMIC VECTORS

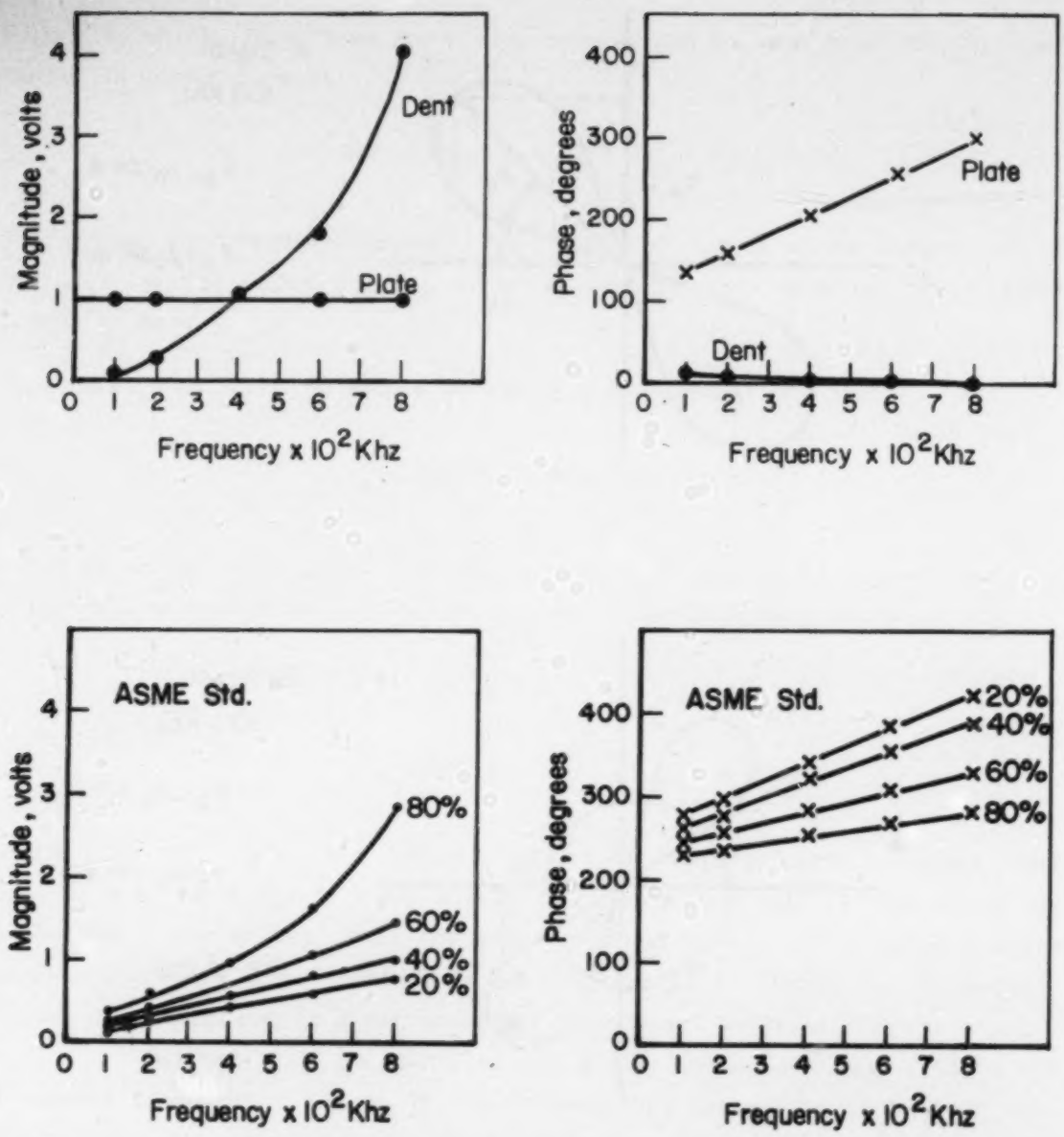


FIGURE 16. MAGNITUDE/PHASE RELATIONSHIPS FOR TYPICAL TUBE VARIABLES NORMALIZED TO ONE VOLT PLATE SIGNAL (0.050" wall tube)

C2 outputs) are scaled and rotated for equal and overlapping dent signals. The simplified approximation of Equation (3) is

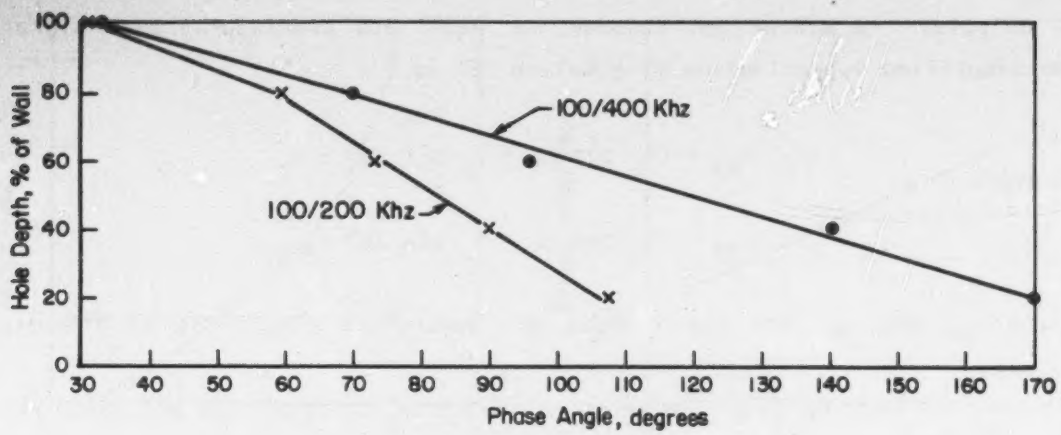
$$x_{AB} = (x_a \cos \Delta\phi + y_a \sin \Delta\phi) - x_b$$
$$y_{AB} = (x_a \cos \Delta\phi - y_a \sin \Delta\phi) - y_b \qquad (4)$$

where x_{ab} and y_{ab} are the inphase and quadrature components at the mixer output.

An important consideration in mixing is the magnitude and phase relationships of the mixer output defect standard signals. Equally important is the magnitude of the residual, i.e., plate or dent. In the simplification made to Equation (3), the residual and defect output signals are being treated independently. Equation (4) was programmed on a computer with input data derived from Figure 16. The computer output data was then screened to select candidate plate mixing frequencies F2 and F3 for the C1 mixer. Evaluational criteria included phase spread and output signal magnitudes.

Plate Suppression

General trends which resulted from the C1 mixer F2/F3 study for 0.050" wall tube are now considered. Basis frequency and mixing frequency combinations were those itemized in Table 1. Frequency combinations involving 500 KHz and greater give too great a phase spread in the sense that the 20 percent defect standard vector either lies on the wobble axis or has rotated beyond it. Low frequency combinations, i.e., 100/200 KHz give compressed phase angle curves, whereas those which include 400 KHz give phase angle curves which are not compressed. Any desired phase angle curve can be achieved by combining a low frequency, i.e., 100 KHz, mixing frequency with the appropriate basis frequency. This is illustrated in Figure 17(a). The 100 KHz contributes very little to the resultant mixer output and essentially acts as a constant vector which is being subtracted from the basis frequency vector data set. This is shown in Figure 17(b) where the 400 KHz/100 KHz defect standard/plate data has been normalized to a 1 volt plate signal.



(a)

Phase Angle Curves

(b)

Vectorial Representation of 100/400 Khz Combination Illustrating How The 100 Khz ASME Std Act as a Constant Vector

FIGURE 17. RANGE OF PHASE ANGLE CURVES THAT CAN BE ACHIEVED USING 100 KHz MIXING FREQUENCY AND DESIRED BASIS FREQUENCY

Another phenomenon which occurs in mixing is the introduction of a mixing loss. If one compares the magnitude of the basis frequency data set vectors with the mixed output resultant, the output is reduced. This is to be expected, since again two vectors $\vec{A}$ and $\vec{B}$ are being subtracted. Figure 18 shows output magnitudes for the 100 percent through 20 percent through wall holes which result for three mixing frequency combinations with a basis frequency of 400 KHz. For reference, the magnitude of the initial 400 KHz basis frequency input is shown. Mixing loss is minimized when the basis frequency/mixing frequency difference is large. As the mixing frequency approaches the basis frequency, the mixing loss increases.

Summarizing up to this point, the mixer output signal can be maximized by appropriate selection of mixing frequency for a given basis frequency. Phase spread is determined primarily by the basis frequency. For 0.050" wall tubing, a 100 KHz/400 KHz combination gives phase spread consistent with the conventional 400 KHz as well as minimizing mixing loss. In multiparameter eddy current, the signal-to-noise ratio given by the ratio of the signal magnitude to extraneous variable residual must be considered. Hence, factors affecting plate residuals must be examined. Figure 19(a) shows RSG plate signals at 100, 200, 400, and 600 KHz. At the lower frequency, the plate signal is somewhat rectangular in shape due to plate permeability. As the frequency is increased, the plate signals become smoother as permeability effects become less pronounced. With a 400 KHz basis frequency, 100 KHz and 200 KHz were selected as mixing frequencies. The resultant plate residuals and the defect standard signals are shown in Figure 19(b). Clearly, a much lower residual is obtained with the 200/400 KHz combination at the expense of phase angle, than the 100/400 KHz case. A higher signal-to-noise ratio also results. Generally, a better residual is obtained when the mixing frequency is chosen close to the basis frequency. Also, with the 100 KHz plate signal, permeability effects predominate in the residual limiting the reduction in plate signal that can be achieved. Initial and weighted plate signals for the two cases are shown in Figure 20.

The previous RSG 0.050" wall tube plate suppression results are now extended to the OTSG 0.040" tube wall thickness. Again, the results of the computer program suggested two possibilities, i.e., a 200/400 KHz combination

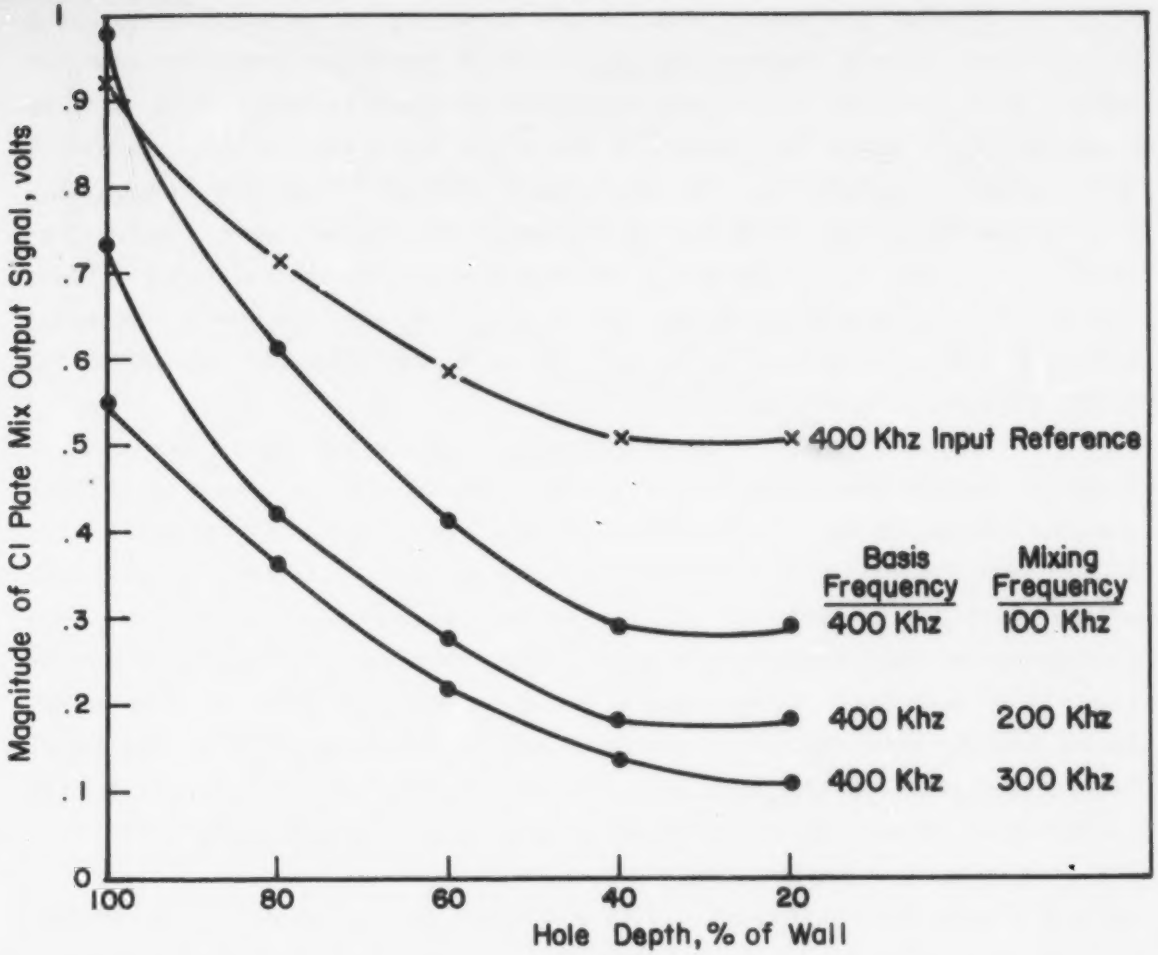
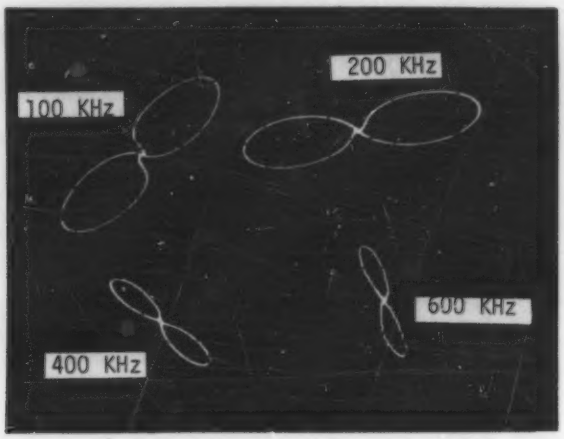
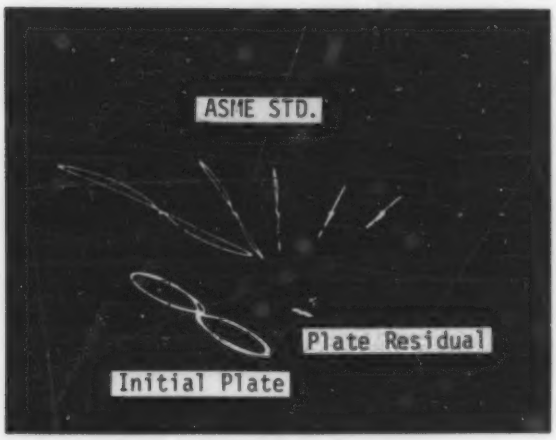


FIGURE 18. MIXING LOSS WHICH RESULTS FROM VECTOR SUBTRACTION IN MIXER OURPUT



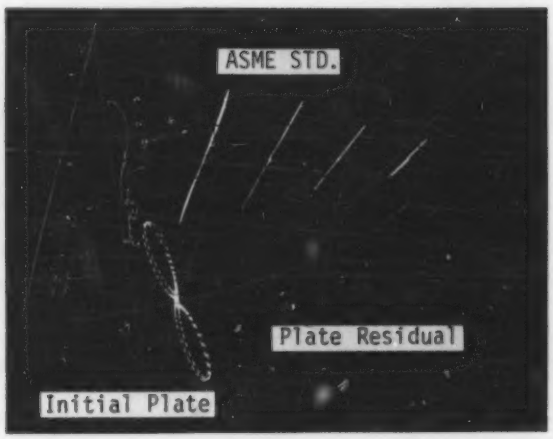
(a)

PLATE SIGNALS AT 100/200/400/600 KHz



(b)

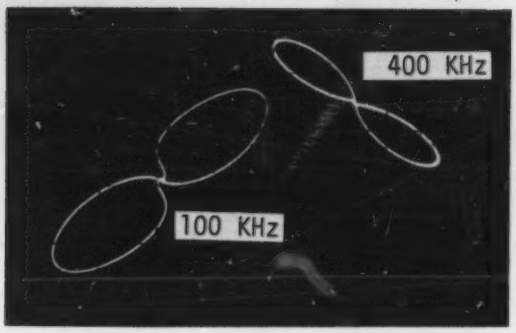
100/400 KHz PLATE SUPPRESSION



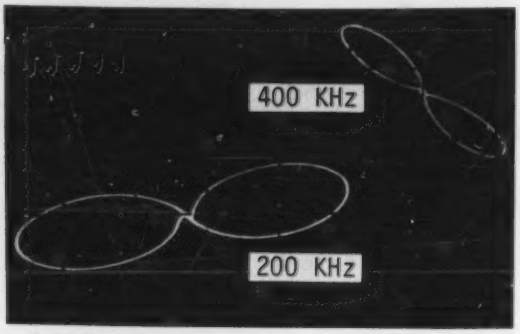
(c)

200/400 KHz PLATE SUPPRESSION

FIGURE 19. PLATE SUPPRESSION MIXES FOR 0.050" WALL TUBING



UNWEIGHTED 100/400 KHz PLATE SIGNALS



UNWEIGHTED 200/400 KHz PLATE SIGNALS

WEIGHTED 100/400 KHz PLATE SIGNALS AND RESIDUAL

WEIGHTED 200/400 KHz PLATE SIGNALS AND RESIDUAL

FIGURE 20. SHAPING OR WEIGHTING OF PLATE SIGNALS

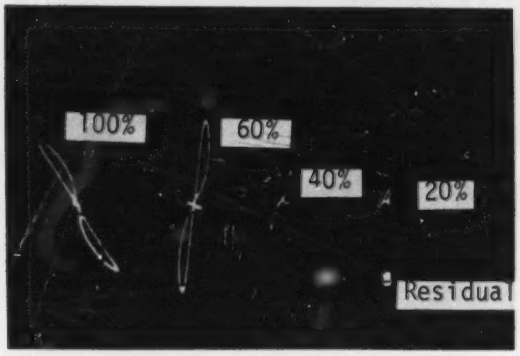
and a 400/600 KHz combination. Even with the thinner wall tubing, 400 KHz is a common basis frequency for the OTSG in-service inspection community and gives a somewhat compressed phase angle curve as compared to the RSG 0.050" wall tube. The 200/400 KHz combination is interesting in that the phase angle curve obtained at the mixed output channel is very similar to the initial 400 KHz. The 400/600 KHz combination was selected for evaluation because the mixed output phase angle curve exhibits more phase spread comparable to the 400 KHz in the thicker wall 0.050" tubing.

Plate suppression results and the resultant defect standard magnitude/phase angle curves are shown in Figure 21 for the 200/400 KHz, 400/600 KHz combinations. The rapid drop-off in signal amplitude for the standard signals is not severe mixing loss but rather reflects the use of a defect standard which is in common use in the OTSG in-service inspection community. On a percentage basis, a better plate reduction is achieved with the 400/600 KHz combination than the 200/400 KHz combination. Phase angle curves for the two mixes are shown in Figure 22.

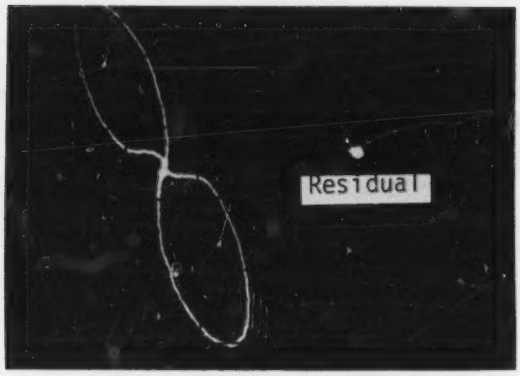
Dent Suppression

Dent suppression is accomplished in the IC3FA C3 mixer utilizing plate free output signals from the C1 and C2 mixers. The plate suppression results have provided candidate F2/F3 frequencies for the C1 mixer which were 100/400 KHz or 200/400 KHz for the 0.048" - 0.050" tube wall thickness range and 200/400 KHz or 400/600 KHz for the 0.040" - 0.042" tube wall thickness range. For a given tube wall thickness range, the particular frequency combination, i.e., 100/400 KHz or 200/400 KHz, is governed by phase spread desires or plate residual considerations. Thus from the initial Table 1 IC3FA mixer sequencing, C1 F2/F3 combinations have been determined. The selection of F1 is determined by the C3 requirements for dent suppression. F1 will also be used in C2 for plate suppression but the C2 mixer primary role is to provide a plate free dent input signal to C3. Hence, the emphasis in the C2 mixer is on a good plate residual. The defect standard signal magnitude/phase angle characteristics in C2 is relatively unimportant since C1 and C3 are the primary signal analysis channels.

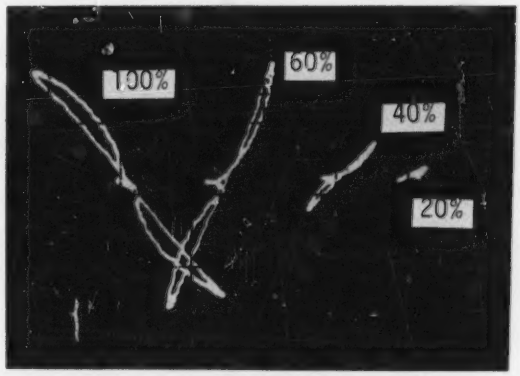
400 KHz PLATE SIGNAL AND PLATE RESIDUAL(200/400 KHz)



OTSG STANDARD AT MIXER OUTPUT (200/400 KHz)



600 KHz PLATE SIGNAL AND PLATE RESIDUAL(400/600 KHz)



OTSG STANDARD AT MIXER OUTPUT (400/600 KHz)

FIGURE 21. OTSG PLATE SUPPRESSION

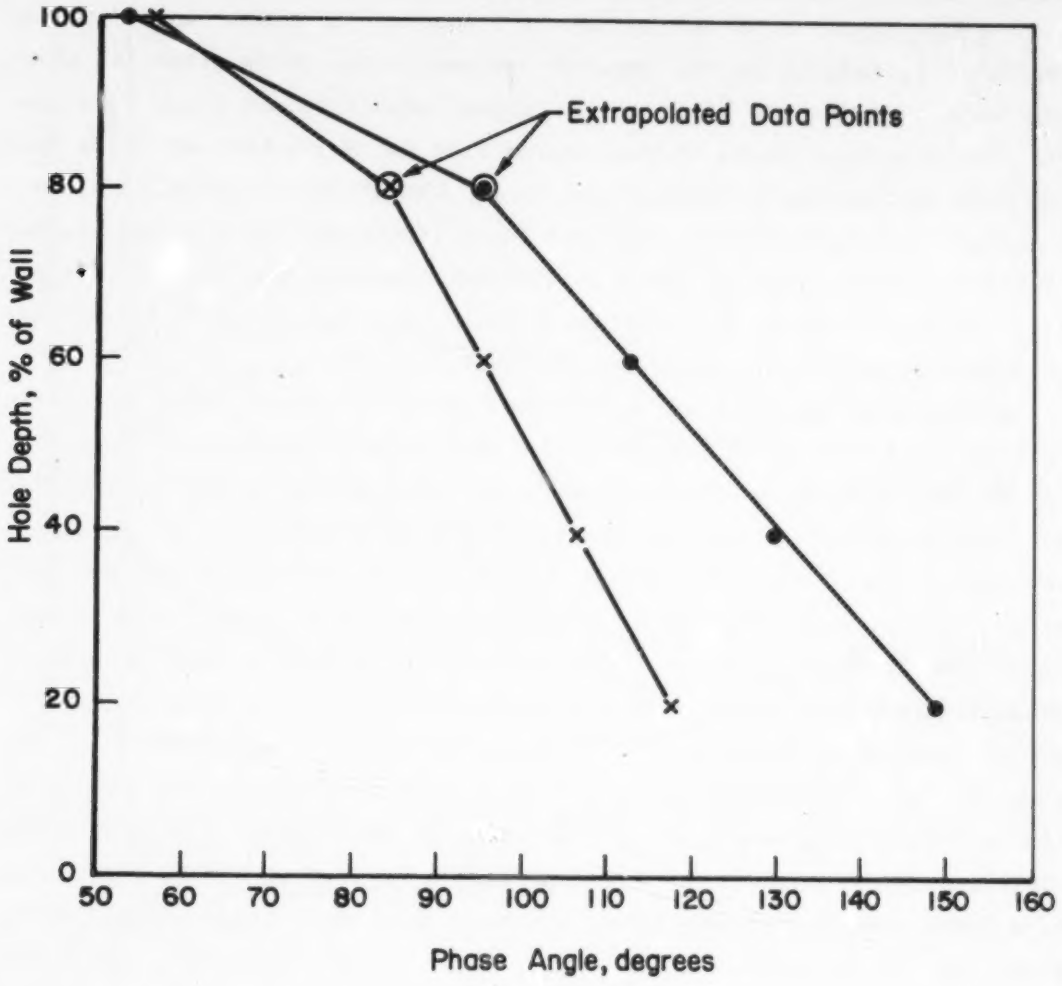


FIGURE 22. DEFECT DEPTH CALIBRATION CURVES USING 200/400 KHz and 400/600 KHz MIXING FREQUENCIES(0.040" wall tube)

The selection of an optimal F1 frequency for 0.050" wall tube was accomplished by relying on the computer implementation of Equation (4) which can be used to calculate mixer output signal magnitude and phase relationships. The data from Figure 16 was renormalized for a constant amplitude dent signal. Cl optimal F2/F3 combinations, i.e., 100/400 KHz or 200/400 KHz were used as the C3 A input signal. The C3 B input signal was variable and assumed the basis frequency range of Table 2 with the exception that 400 KHz was excluded. This is because F2 in C2 has already been determined to be 400 KHz and F1 cannot equal F2 for use in the C2 mixer.

The resultant C3 mixer output ASME defect standard signal magnitude variations normalized for a one-volt input dent signal are shown in Figure 23. As can be seen, a wide variation in magnitude relations can occur for the different combinations. In general, as the dent mixing frequency is increased, larger output signals result. With the exception of the 100/400/200 KHz combination, fairly large phase spread was achieveable which tended to be independent of the F1 frequency. For the latter combination, a very compressed phase angle curve resulted. From a practical standpoint, a lower upper frequency is desirable, hence an F1 frequency of 600 KHz was selected. The results for the 100/400/600 KHz combination dent suppression mix is illustrated in Figure 24(a) where are illustrated the ASME defect standard, plate residual and dent residuals for 2 mil through 8 mil radial dents. As can be seen, a large amount of phase spread exists. Good dent signal reduction is obtained for up to about a 6 mil radial dent. For comparison, the input signal to noise ratio can be seen from Figure 24(b) where are illustrated the conventional 400 KHz ASME standard signals, the plate and the 2 through 8 mil radial dents. The Figure 24(b) photograph was taken at an intentionally reduced sensitivity to illustrate the magnitude of the dent signals.

For the 200/400/600 KHz dent suppression combination, comparable reduction in the dent signal can be achieved but the phase spread in the mixed output channel is not nearly as good as the 100/400/600 KHz combination. See Figure 24(c).

Dent suppression in the OTSG 0.040" wall tubing was not examined using the computer analysis. By extrapolating from the 0.050" wall tubing dent suppression analysis, probable frequency combinations F1, F2 and F3 are

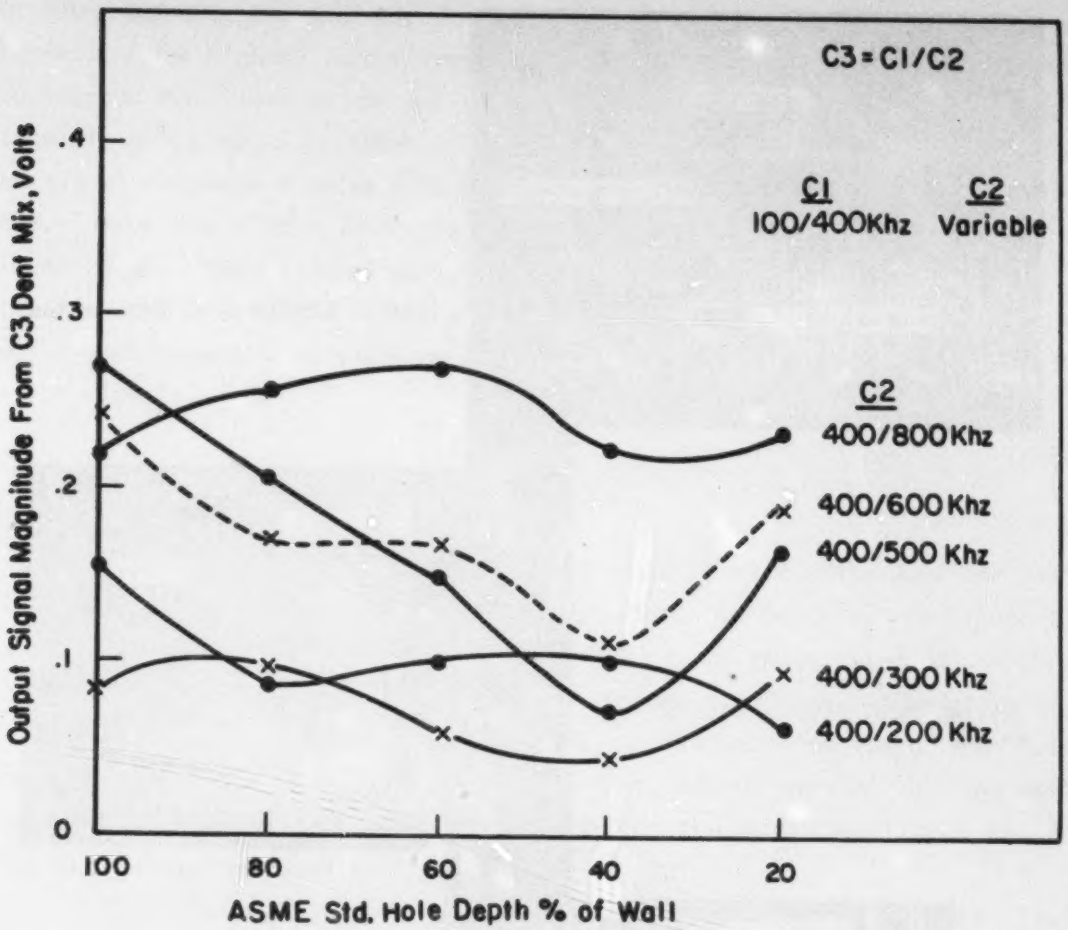
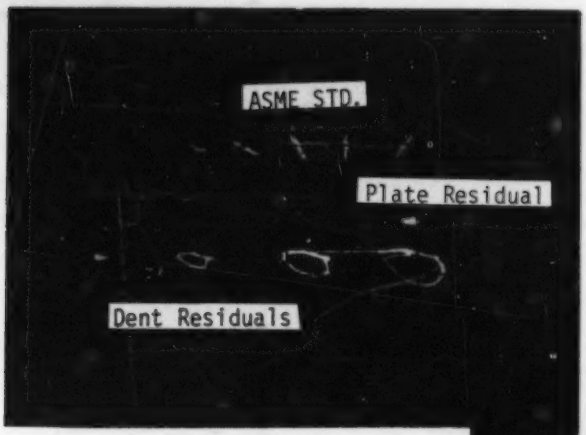
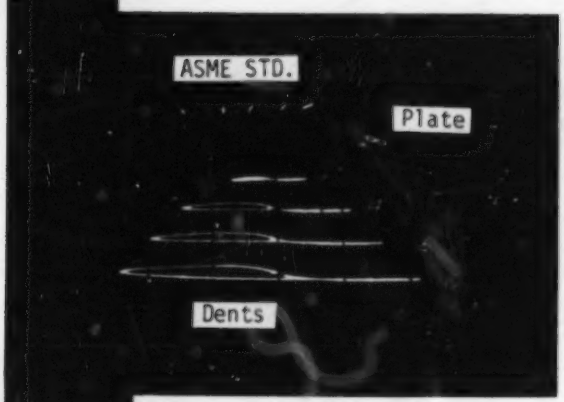


FIGURE 23. C3 MIXER OUTPUT SIGNAL MAGNITUDE FOR SELECTED F1 MIXING FREQUENCIES(ASME STANDARD)



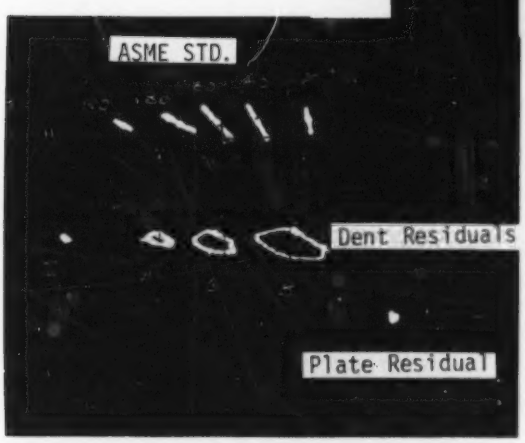
(a)

100/400/600 KHz Dent Suppression



(b)

INITIAL INPUT SIGNAL-TO-NOISE RATIO



(c)

200/400/600 KHz DENT SUPPRESSION

FIGURE 24. DENT SUPPRESSION

800 KHz, 600 KHz and 400 KHz for good phase spread in the C3 mixer output channel. The highest IC3FA frequency card available was 600 KHz hence a 200/400/600 KHz combination was experimentally examined. The initial input signal-to-noise ratio is shown in Figure 25(a) and (b) where are illustrated the signal response from an OTSG standard and the signal from a thirteen-volt dent. Note the Figure 25(b) is shown at half the sensitivity setting as Figure 25(a). The C3 mixed output channel is shown in Figure 25(c) where are illustrated the output from the defect standard and the dent residual. Good dent signal reduction is obtained but there is very little phase spread in the defect signals.

Mix Evaluation

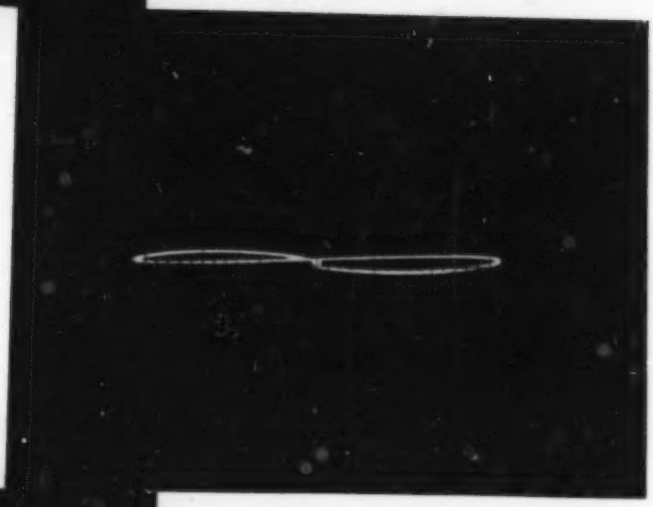
Further assessment of candidate C1 mixer F2/F3 combinations for plate suppression was made using the two sets of standards described in Figure 11. The conventional single frequency 400 KHz response of these standards is shown in Figure 26. Figure 26(a) illustrates a typical 0.050" wall tube plate signal along with the variable amplitude signals, obtained from one to four holes at the three depths of 20 percent, 40 percent, and 60 percent of tube wall. Figure 26(b) illustrates the same condition for the 0.040" wall tube and the broached plate signal.

Selected 0.050" wall tube 100/400 KHz evaluation results are illustrated in Figures 27 and 28. Figure 27 shows the eddy current signals which are obtained from the C1 mixer output as the 20 percent depth hole series is stepped through the support plate. For the case of two to four holes of 20 percent depth, defect detection is straightforward. For the case of a single 20 percent hole, it is difficult to detect the hole within the plate residual. Figure 28 shows the C1 mixer eddy current signals for a single 40 percent and 60 percent through wall hole. Here, defect detection is straightforward.

Results for the 0.050" wall tube 200/400 KHz F3/F2 combination are now presented. Figures 29 and 30 shows the results obtained when various numbers of holes at selected depths are stepped through the plate. The effect of a much better residual is apparent from Figure 29, where the single 20 percent through wall hole is readily detectable within the residual.

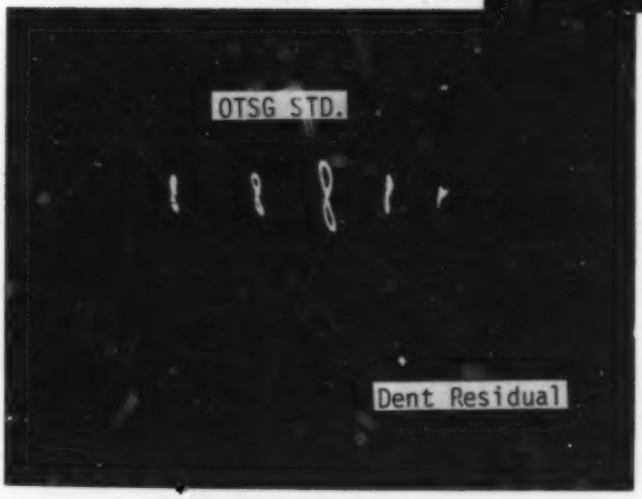
(a)

OTSG STANDARD(400 KHz) 1v/div.



(b)

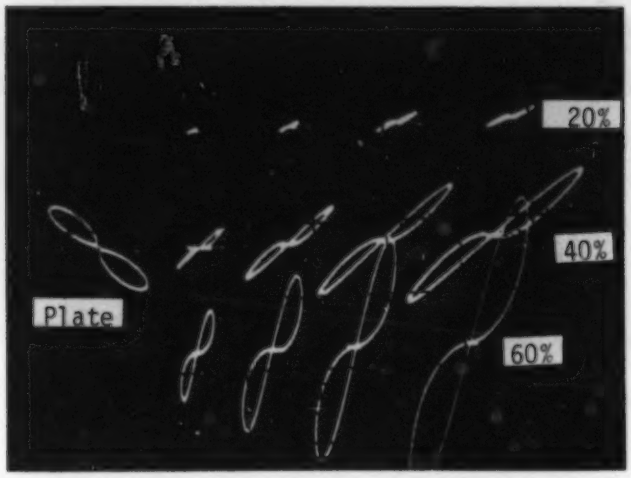
DENT SIGNAL AT 400 KHz 2V/div.



(c)

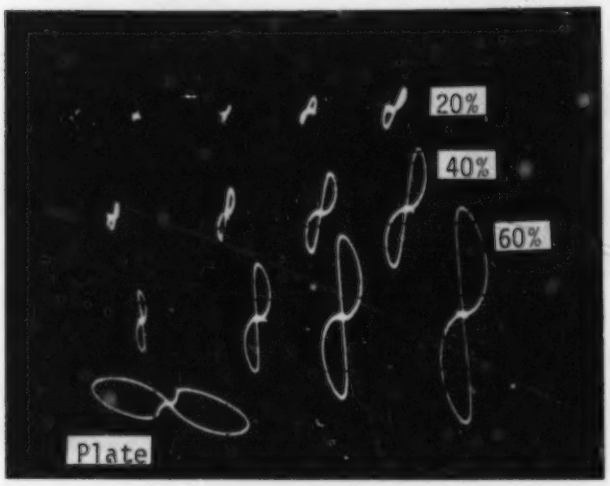
200/400/600 KHz OTSG DENT MIX.
STANDARD SIGNALS AND DENT RESIDUAL

FIGURE 25. OTSG DENT SUPPRESSION



(a)

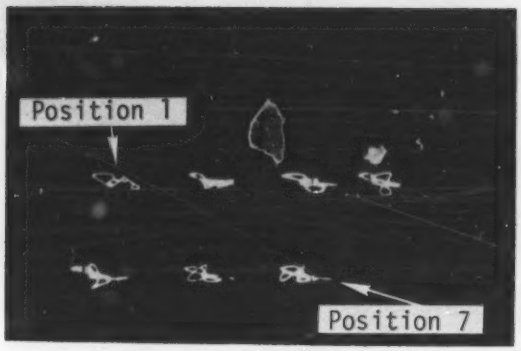
400 KHz PLATE SIGNAL AND VARIABLE AMPLITUDE DEFECT SIGNALS. (0.050" WALL TUBE)



(b)

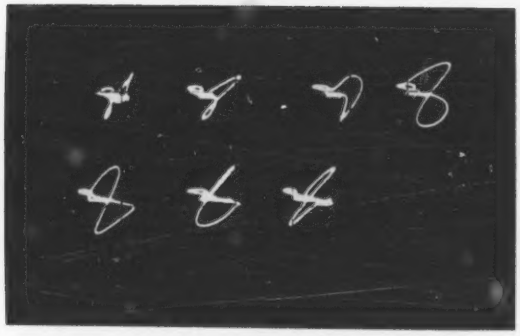
400 KHz PLATE SIGNAL AND VARIABLE AMPLITUDE DEFECT SIGNALS. (0.040" WALL TUBE)

FIGURE 26. SIGNAL AMPLITUDES USED FOR MIX EVALUATION



1 x 20%

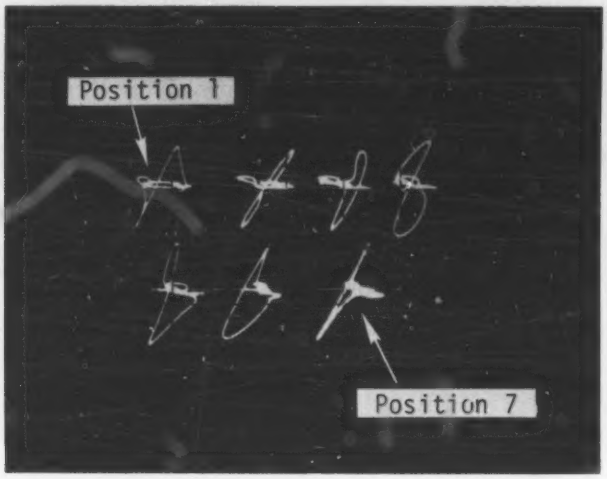
2 x 20%



3 x 20%

4 x 20%

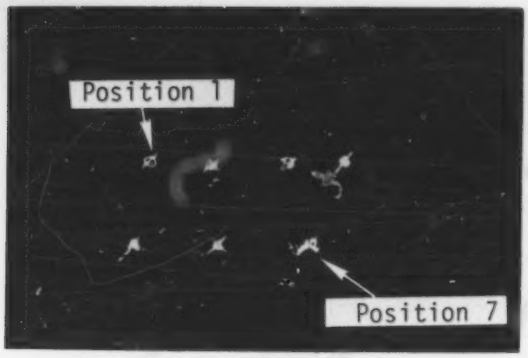
FIGURE 27. DEFECT SIGNALS WITHIN 100/400 KHz PLATE RESIDUAL



1 x 40%

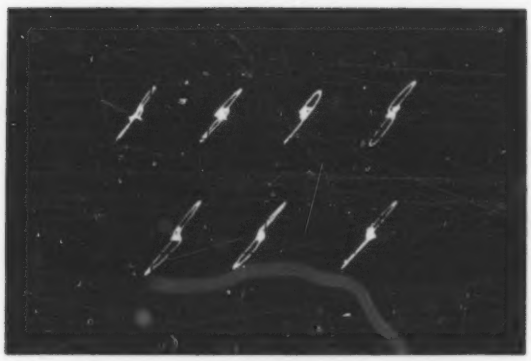
1 x 60%

FIGURE 28. DEFECT SIGNALS WITHIN 100/400 KHz PLATE RESIDUAL



1 x 20%

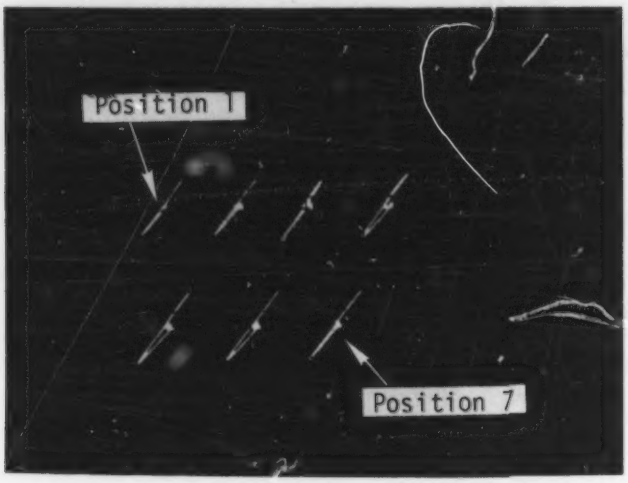
2 x 20%



3 x 20%

4 x 20%

FIGURE 29. DEFECT SIGNALS WITHIN 200/400 KHz PLATE RESIDUAL



3 x 40%

4 x 60%

FIGURE 30. DEFECT SIGNALS WITHIN 200/400 KHz PLATE RESIDUAL

Mixing error for the two candidate plate mixes was estimated using the signal patterns corresponding to the ASME Section XI standard which are the four 20 percent depth holes, and single 40 percent and 60 percent depth holes. Estimated defect depth error is shown in Figure 31. The 200/400 KHz results show less scatter than the 100/400 KHz combinations which means that the resultant error is less dependent on where the defect signal is positioned with respect to the support plate.

Results for the OTSG 0.040" nominal wall thickness tubing 200/400 KHz combinations are now considered. C1 mixer output eddy current signals for the OTSG standard, described in Figure 11, stepped through the plate are shown in Figures 32 through 34. For the 40 percent and 60 percent through wall hole depth, defect detection is readily achieved. For the 20 percent through wall holes, the 4 x 20 percent combination exhibits good signal-to-noise ratio; the 3 x 20 percent combination can be detected although there is considerable signal distortion caused by the plate residual. For the single and double hole 20 percent combination, the plate residual masks the defect signal.

Better detection capability was exhibited with the 0.040" wall tube 400/600 KHz combination. Figures 35 through 37 shown the C1 mixer output signals for various numbers of holes at depths of 20 percent, 40 percent and 60 percent of tube wall. The plate residual does not significantly distort the defect signals, and defect detectability is improved which can be seen by comparing the 20 percent through wall hole combinations with 200/400 KHz situation.

Mixing error for the two candidate OTSG plate mix combinations, i.e., 200/400 KHz and 400/600 KHz is shown in Figure 38. The 400/600 KHz results exhibit less scatter which again implies that the error is not dependent on where the defect is located within the broached plate.

Dent mixing error estimates were identified using the Combustion Engineering 0.048" wall tubing with the specimen configurations shown in Figure 12. The 100/400/600 KHz dent mix was selected for further evaluation because of its phase spread characteristics. Dent sizes varied between 2 mils and 8 miis radial, and through wall hole depths of 40 percent and 60 percent were placed at the outside plate/dent edge, and centered within the dent.

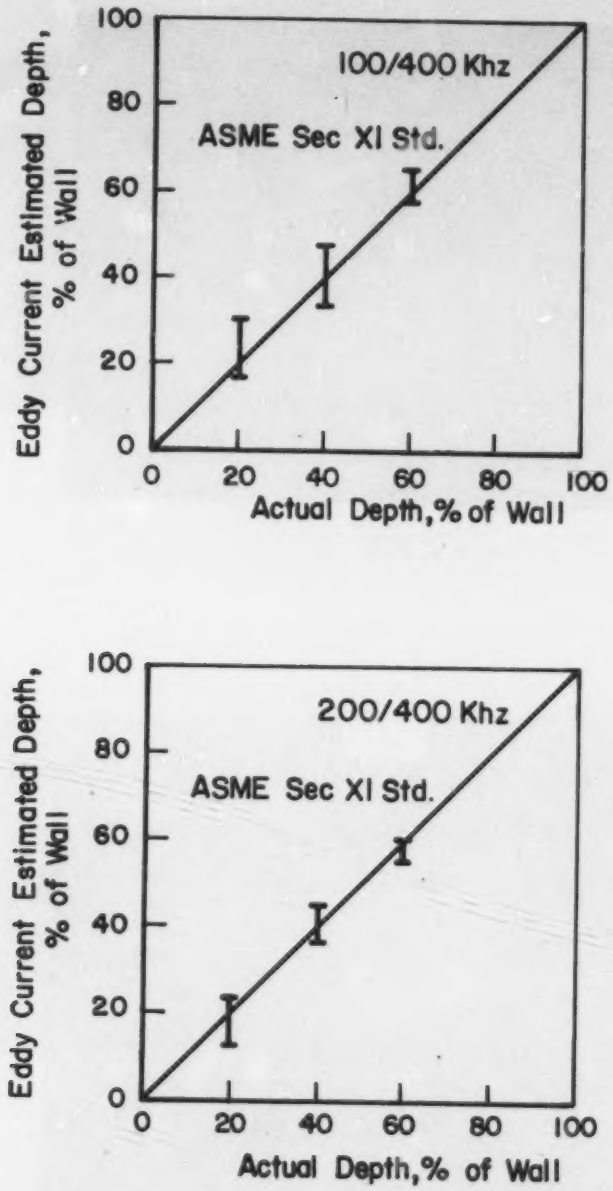
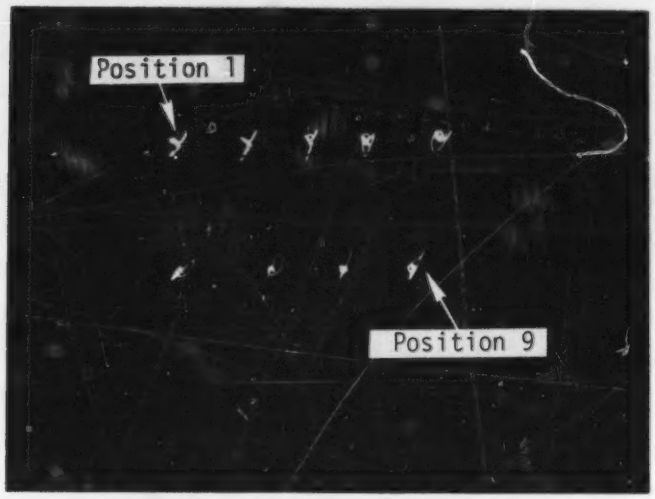
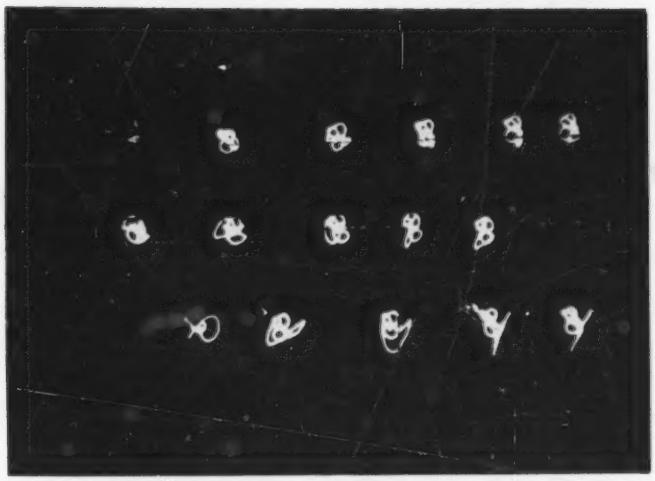


FIGURE 31. ESTIMATED MIXING ERROR FOR RSG PLATE SUPPRESSION (0.050" wall tube)



4 x 20%

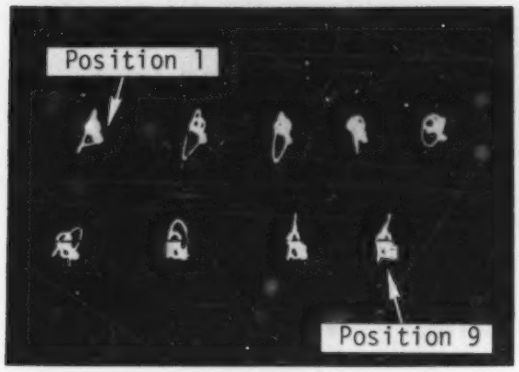


2 x 20%

1 x 20%

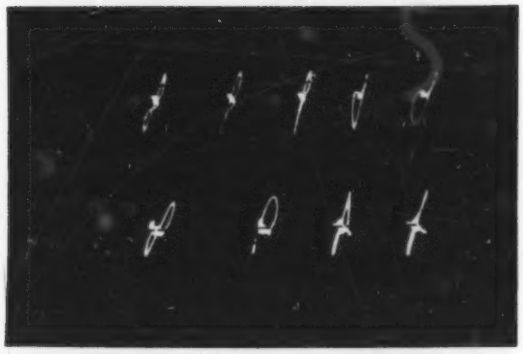
3 x 20%

FIGURE 32. DEFECT SIGNALS WITHIN 200/400 KHz PLATE RESIDUAL

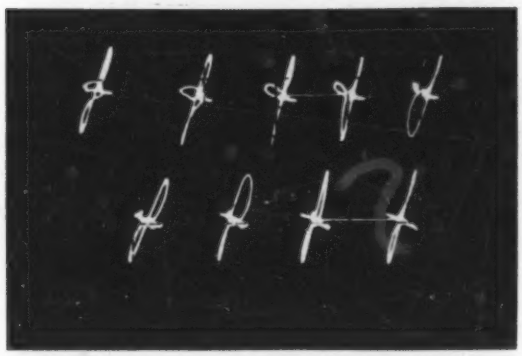


1 x 40%

2 x 40%

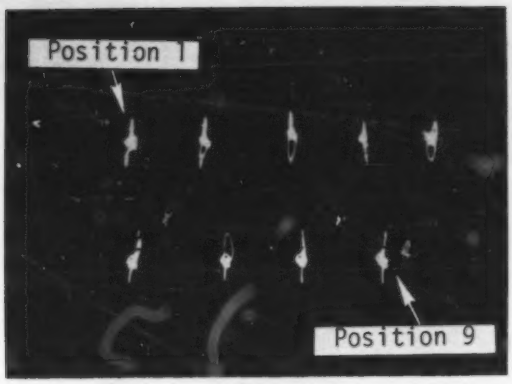


3 x 40%

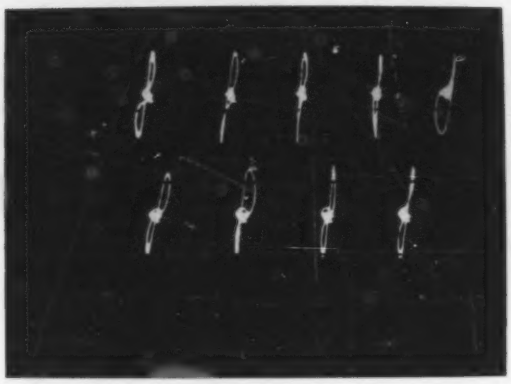


4 x 40%

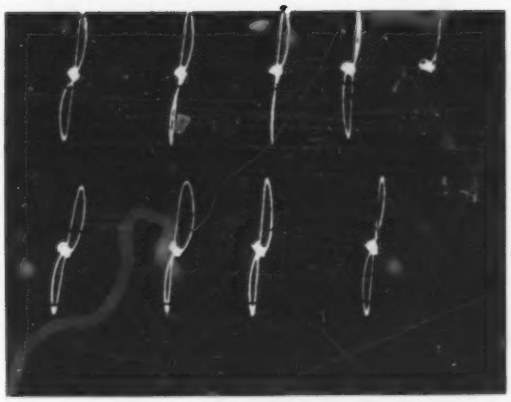
FIGURE 33. DEFECT SIGNALS WITHIN 200/400 KHz PLATE RESIDUAL



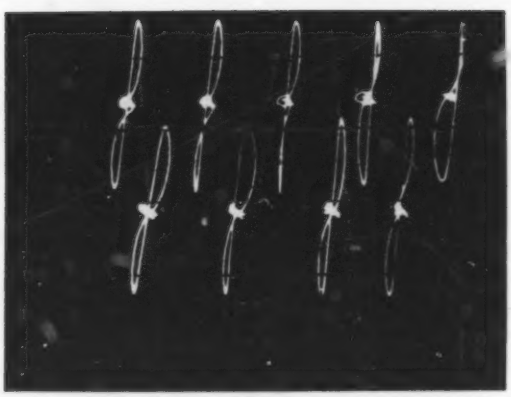
1 x 60%



2 x 60%

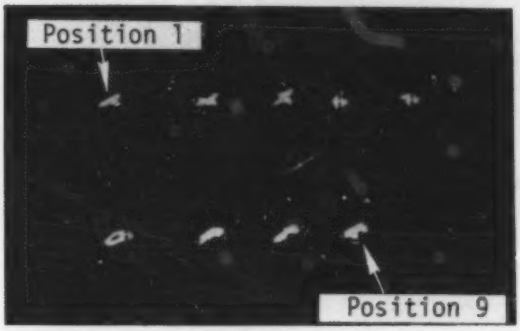


3 x 60%



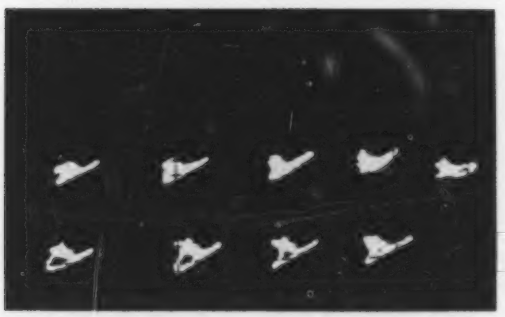
4 x 60%

FIGURE 34. DEFECT SIGNALS WITHIN 200/400 KHz PLATE RESIDUAL



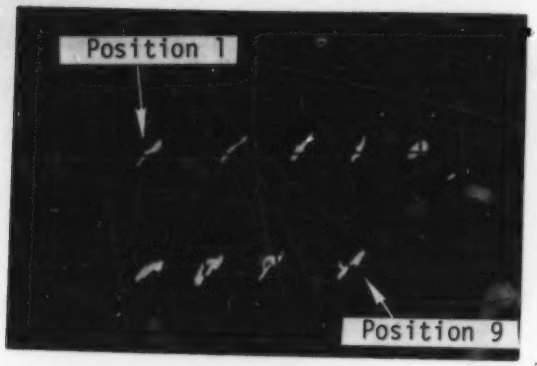
2 x 20%

3 x 20%

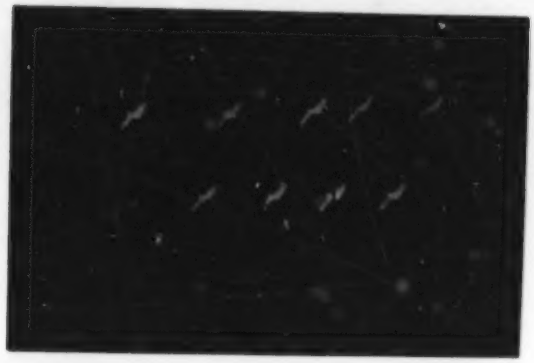


4 x 20%

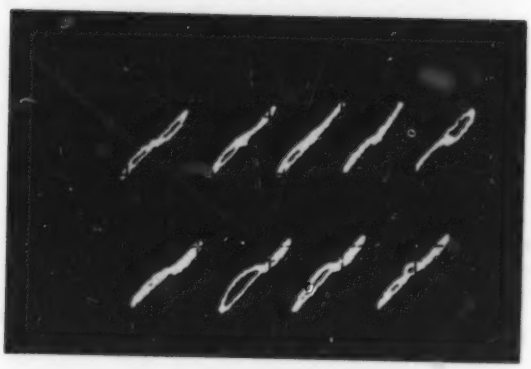
FIGURE 35. DEFECT SIGNALS WITHIN 400/600 KHz PLATE RESIDUAL



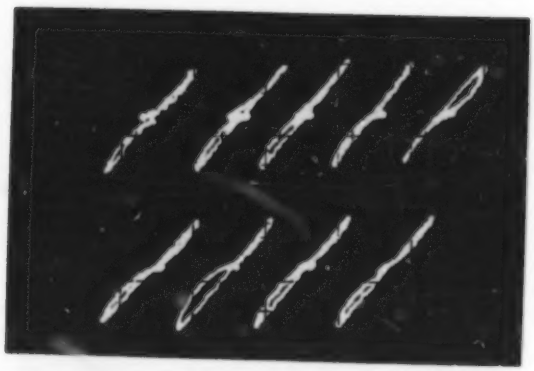
1 x 40%



2 x 40%

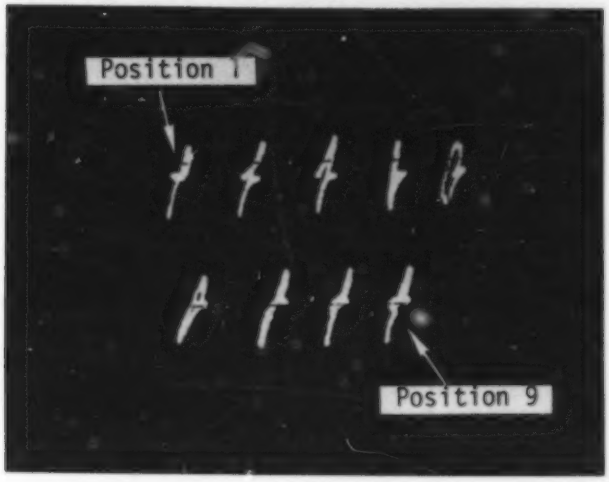


3 x 40%



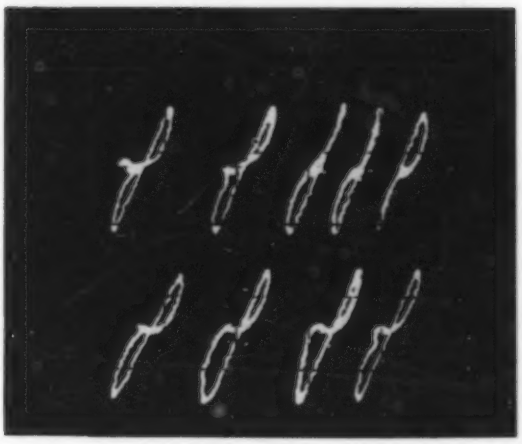
4 x 40%

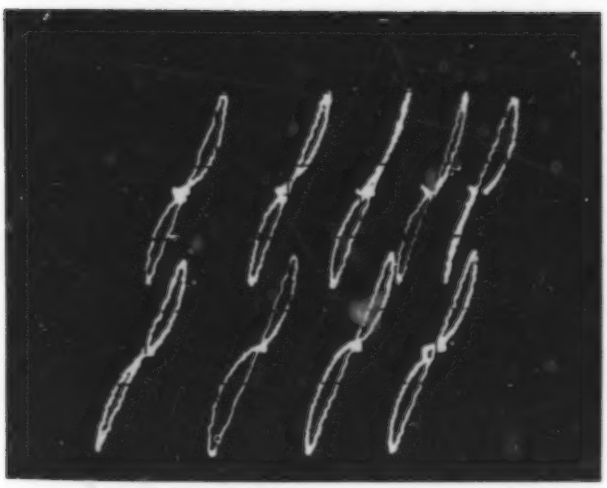
FIGURE 36. DEFECT SIGNALS WITHIN 400/600 KHz PLATE RESIDUAL



1 x 60%

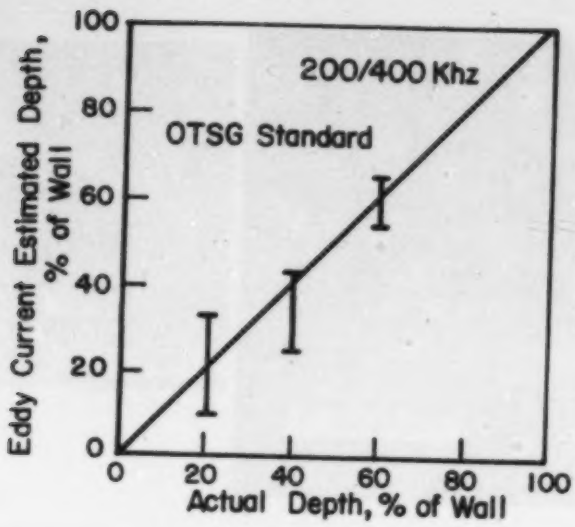
2 x 60%





3 x 60 %

FIGURE 37. DEFECT SIGNALS WITHIN 400/600 KHz PLATE RESIDUAL



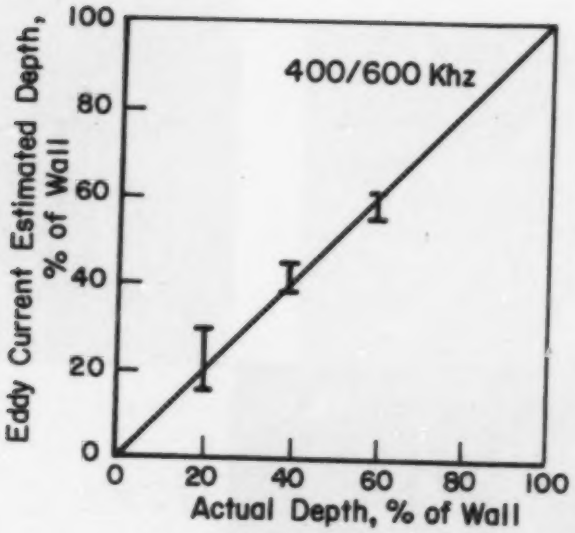


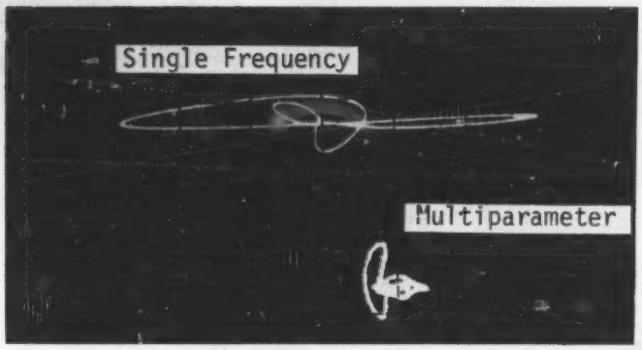
FIGURE 38. ESTIMATED MIXING ERROR FOR OTSG PLATE SUPPRESSION (0.040" wall tube)

Figure 24(a) shows dent residuals and the C3 mixer response to the ASME Section XI standard. Figures 39 and 40 show the mixer output for the 40 percent defect at the plate/dent edge and centered within the dent. Figures 41 and 42 show the output for the 60 percent defect under the same test conditions. For comparison, the conventional single frequency 400 KHz response is shown at the upper part of each photograph. In all cases, defect detection is readily achieveable and the depth measurement error in estimating defect depth is tabulated in Figure 43(a). The error is considered to be quite reasonable considering the test conditions. The 100/400/600 KHz dent mix phase angle versus defect depth calibration curve is also shown in Figure 43(b).

Defect Depth Measurement Accuracy

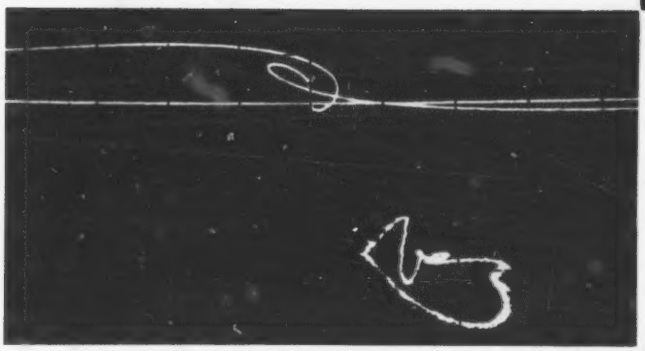
Continued assessment of various plate mixes was made using simulated steam generator tubing defects of various geometries and depths. The defect types and associated geometries are shown in Figures 13 and 14.

For RSG's, defect types evaluated included wastage, pitting and cracking. Eddy current signals at 400 KHz and the 100/400 KHz plate mix are shown in Figure 44 for the wastage placed at the support plate edge. Also shown are the 400 KHz wastage signals free of the plate signal. In general the wastage signal is relatively large. Figure 45(a) and (b) illustrate distorted support plate signals and the mixed output for the 100/400 KHz combination for simulated tube cracking (EDM notch) at the support plate. The EDM notches were 3/4 of an inch in length and were centered within the plate. The 100/400 KHz combination signals for the notches in Figure 45(b) are somewhat distorted by the plate residual as evidenced by the ballooning of the signals. By comparison, Figure 45(c) shows the mixed output for the 200/400 KHz combination for the same series of EDM notches centered within the plate. Also shown is the plate residual. Much less signal distortion results with the latter combination. The 40 percent notch signal shown in Figure 45(c) could not be reliably detected and characterized using the 100/400 KHz combination. Figures 46 and 47 show respectively the mixed output response for the 100/400 KHz combination for simulated pitting located within the support plate. Also

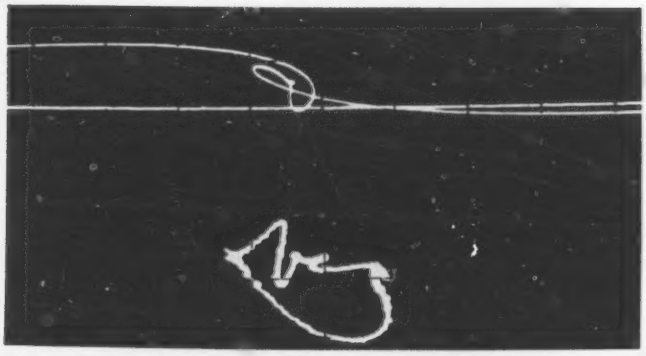


2 mil dent

4 mil dent



6 mil dent



8 mil dent

FIGURE 39. 100/400/600 KHz DENT SUPPRESSION FOR 40% ASME HOLE AT DENT/PLATE EDGE

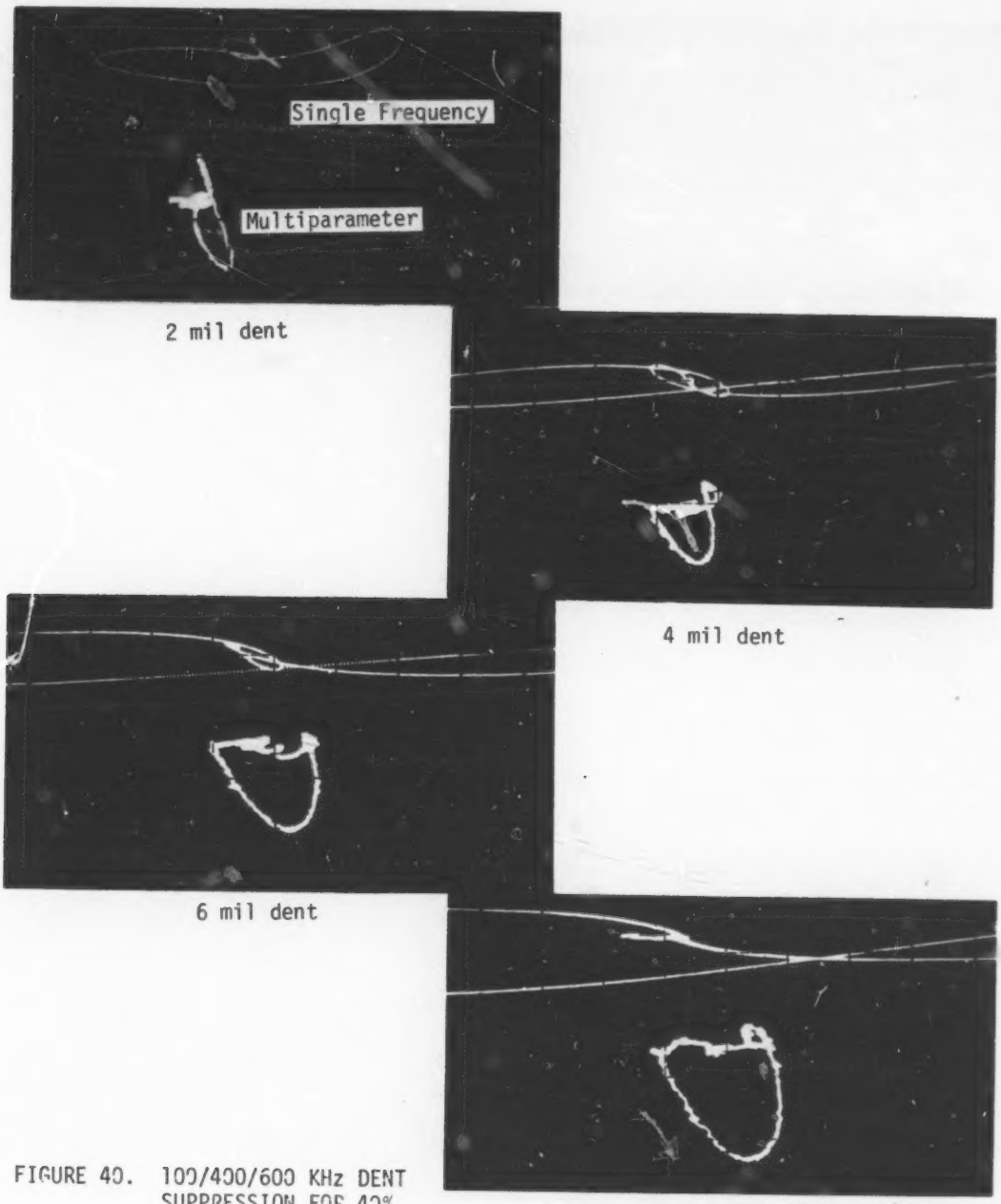
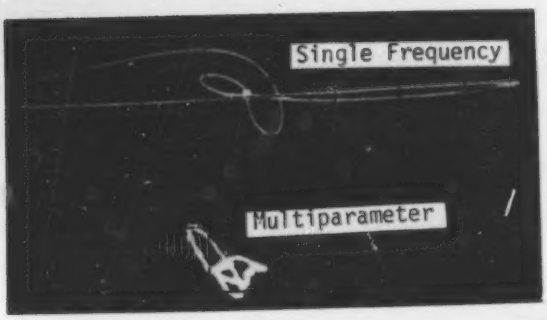
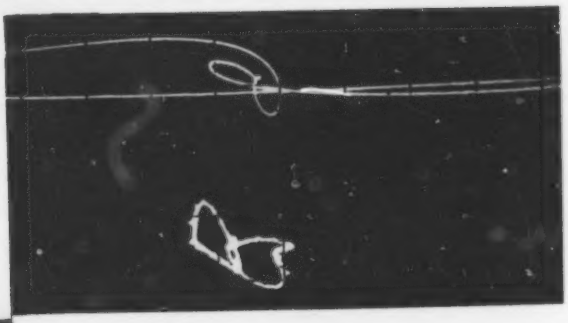


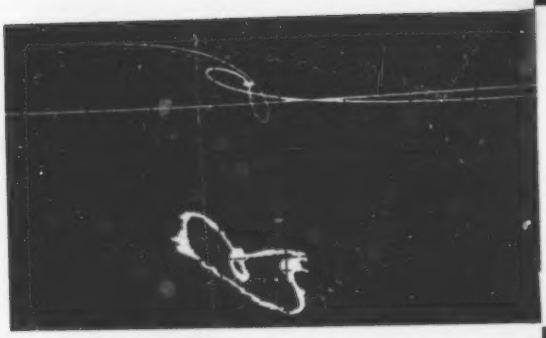
FIGURE 40. 100/400/600 KHz DENT SUPPRESSION FOR 40% ASME HOLE CENTERED IN DENT



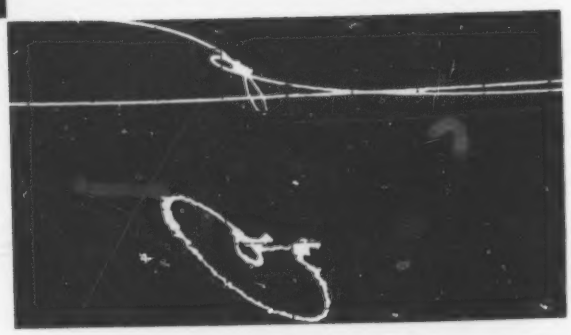
2 mil dent



4 mil dent



6 mil dent



8 mil dent

FIGURE 41. 100/400/600 KHz DENT SUPPRESSION FOR 60% ASME HOLE AT DENT/PLATE EDGE.

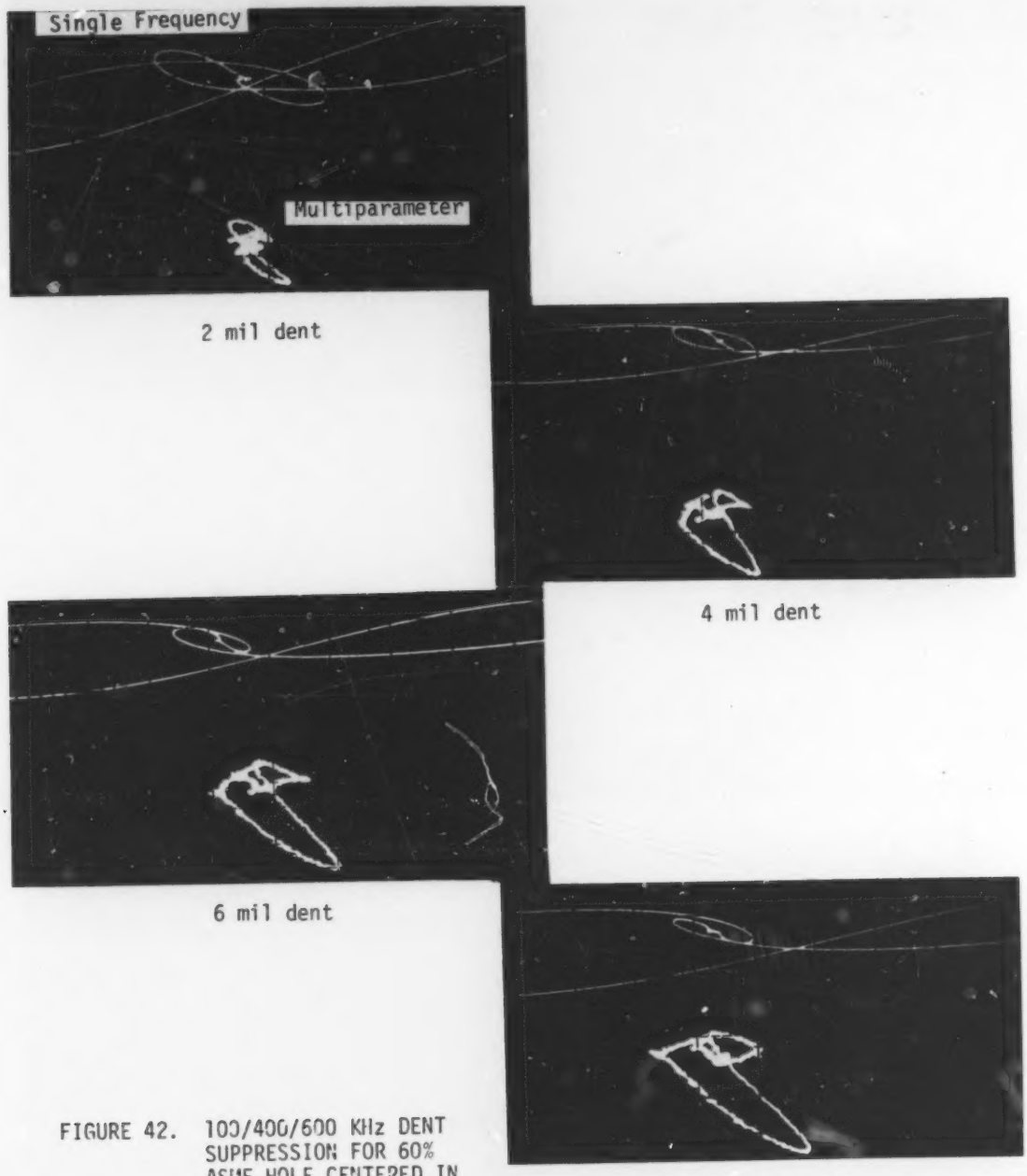
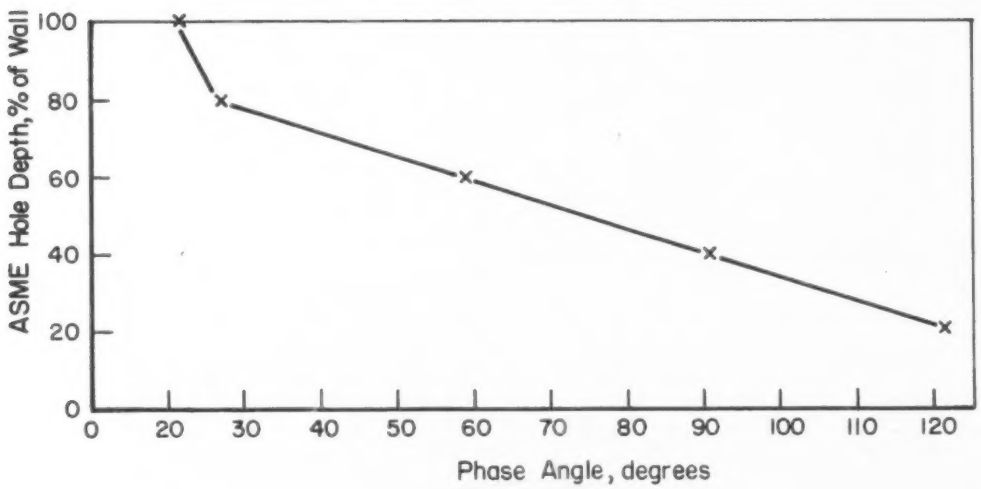


FIGURE 42. 100/400/600 KHz DENT SUPPRESSION FOR 60% ASME HOLE CENTERED IN DENT.

Hole Depth, % of Wall	Dent Size, Radial Mils	Eddy Current Estimated Depth, % of Wall	
		Edge	Center
40%	2	40	50
	4	30	49
	6	35	49
	8	34	51
60%	2	62	71
	4	56	60
	6	65	66
	8	75	68

(a)

DEPTH ESTIMATION ACCURACY



(b)

DEPTH CALIBRATION CURVE

FIGURE 43. DENT SUPPRESSION FLAW DEPTH ESTIMATION AND 100/400/600 KHz PHASE ANGLE CURVE

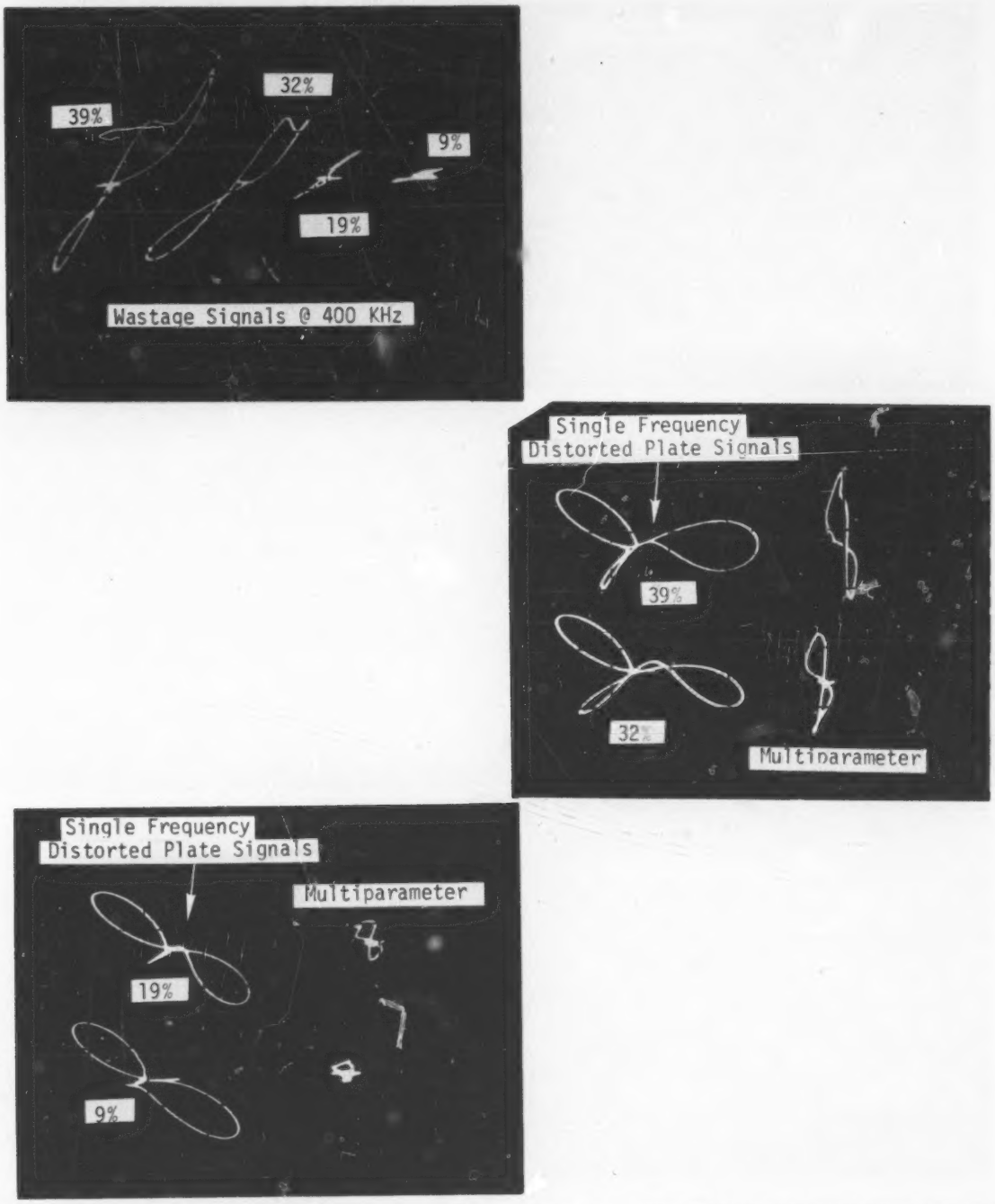
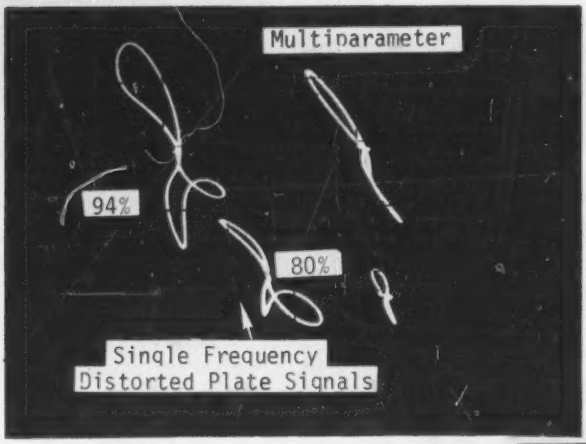
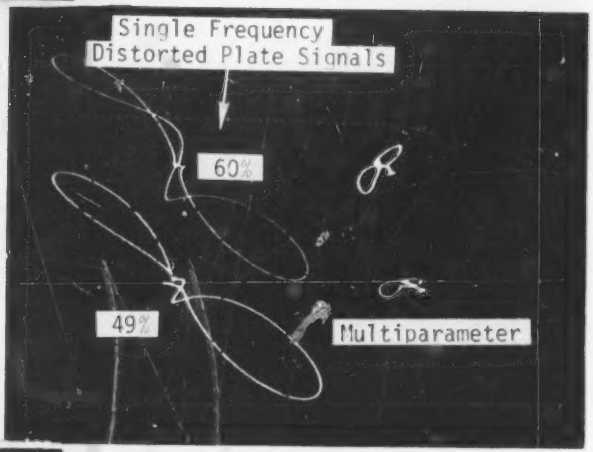


FIGURE 44. MULTIPARAMETER CHARACTERIZATION OF WASTAGE AT SUPPORT PLATE.



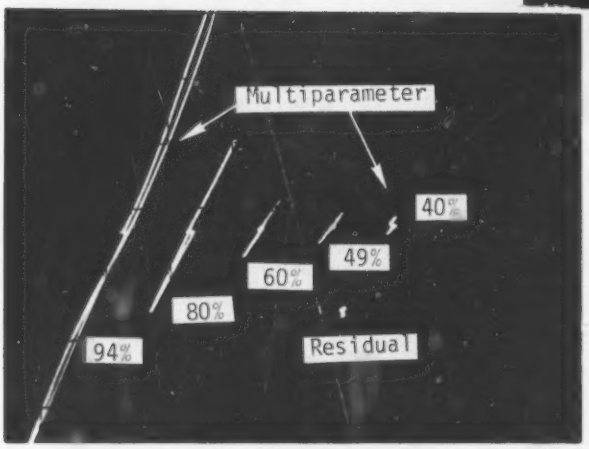
(a)

SIMULATED CRACK
CHARACTERIZATION
100/400 KHz



(b)

SIMULATED CRACK
CHARACTERIZATION
100/400 KHz



(c)

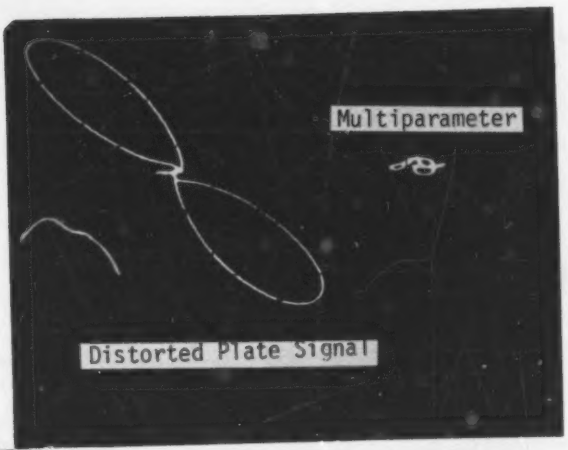
SIMULATED CRACK
CHARACTERIZATION
200/400 KHz

FIGURE 45. MULTIPARAMETER CHARACTERIZATION OF SIMULATED CRACKS AT SUPPORT PLATE

100/400 KHz Plate
Suppression

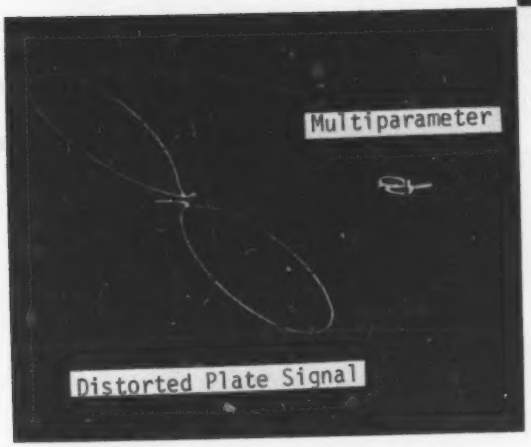
(a)

80% Through Wall
Pit Located at Plate



(b)

70% Through Wall
Pit Located at Plate

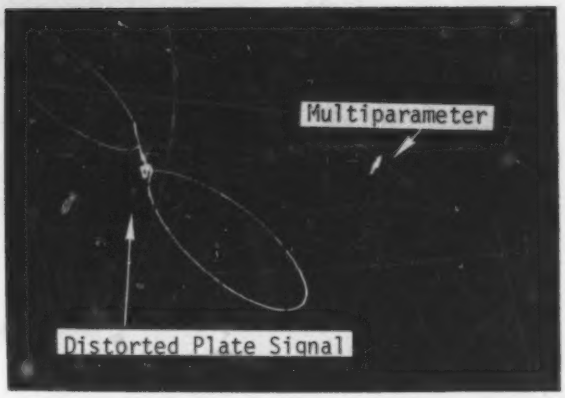


(c)

50% Through Wall
Pit Located at Plate

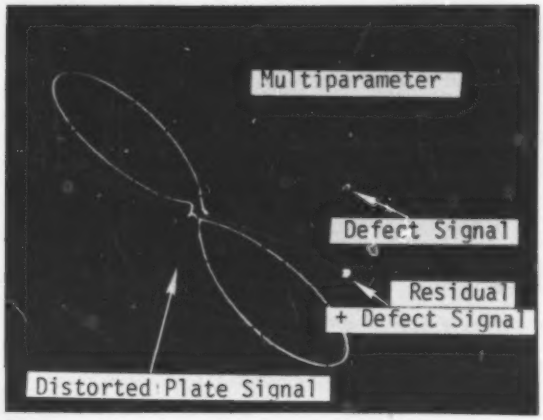
FIGURE 46. MULTIPARAMETER CHARACTERIZATION OF PITTING AT SUPPORT PLATE.

200/400 KHz Plate
Suppression



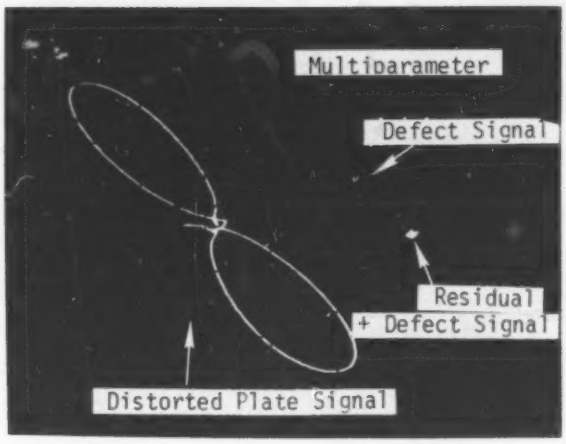
(a)

80% Through Wall
Pit Located at Plate



(b)

70% Through Wall
Pit Located at Plate



(c)

50% Through Wall
Pit Located at Plate

FIGURE 47. MULTIPARAMETER CHARACTERIZATION OF PITTING AT SUPPORT PLATE.

shown are the distorted plate signals at the normal 400 KHz. By comparing mixed output responses for the two cases, a much lower residual is obtained using the 200/400 KHz combination. In Figure 47(b) and (c), the defect signal has been separated out of the residual in addition to showing the residual and defect signal combined.

Depth measurement accuracy estimates for the RSG defect types considered previously are shown in Figure 48. Illustrated are results for the 400 KHz single frequency for defects free of the support plate in addition to the results for the two mix combinations with the defects located in proximity to the plate. Data trends which are exhibited in Figure 48 are now considered. For the 400 KHz results, there is a tendency to overestimate wastage and underestimate the notch and pits. This result has been confirmed experimentally elsewhere and also confirmed by the correlation of eddy-current-derived depth information on tubes pulled from steam generators. The reason for the overestimation/underestimation phenomenon is the use of the ASME Section XI standard for the derivation of a phase angle versus defect curve. The configuration of the standard was chosen to offer a compromise in depth estimates for the large volume/small volume defect types. The 100/400 KHz results show a similar trend to overestimation/underestimation but the scatter is more pronounced. Part of the scatter for the shallower pits and notches can be attributed to mixing error which results from the rather large plate residual for the 100/400 KHz combination. The reason for the additional bias in the overestimation of wastage is not understood. The 200/400 KHz results again show a similar trend in underestimation/overestimation but the scatter is less pronounced for the small volume defects. This is attributed to lower mixing error resulting from the smaller 200/400 KHz residual.

Distorted 400 KHz plate signals, and mixer output for the 400/600 KHz combination, for typical OTSG defect types, are shown in Figure 49. Figure 49(a) illustrates signals obtained from fretting while Figure 49(b) shows signal responses from the erosion/corrosion or teardrop defect. Figure 49(c) shows the signal which results from the multiple scalloping defect whereas Figure 49(d) shows an example of pitting. Estimated depths for representative OTSG defect types at various depths is shown in Figure 50 for both the 200/400 KHz plate mix and the 400/600 KHz plate mix. Comparable results were obtained

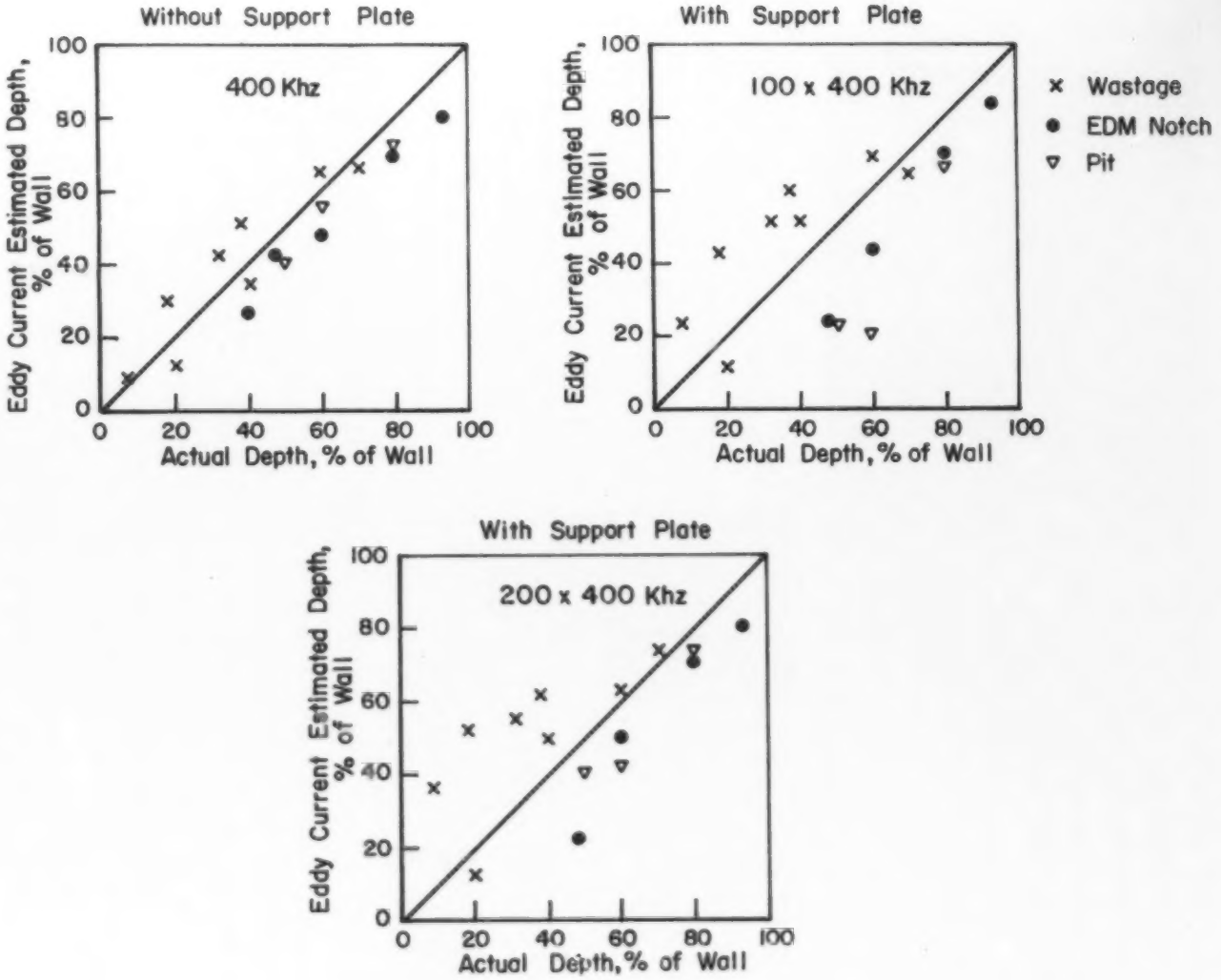
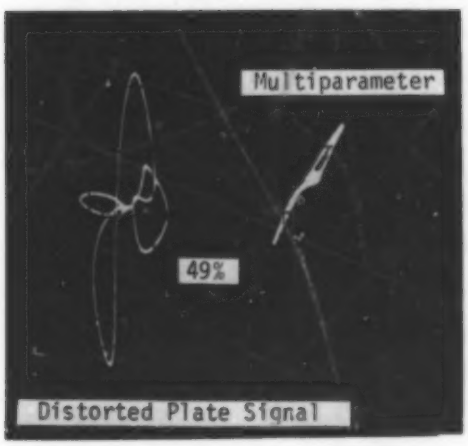


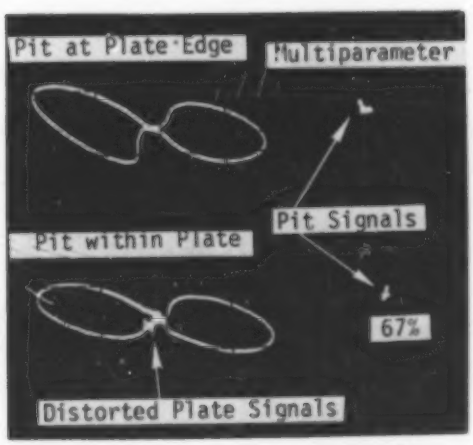
FIGURE 48. SCATTER PLOT OF ACTUAL DEFECT DEPTH VERSUS EDDY CURRENT ESTIMATED DEPTH FOR RSG DEFECT TYPES.

Fretting

Erosion/Corrosion



Scalloping



Pitting

FIGURE 49. MULTIPARAMETER CHARACTERIZATION OF OTSG DEFECTS AT SUPPORT PLATE

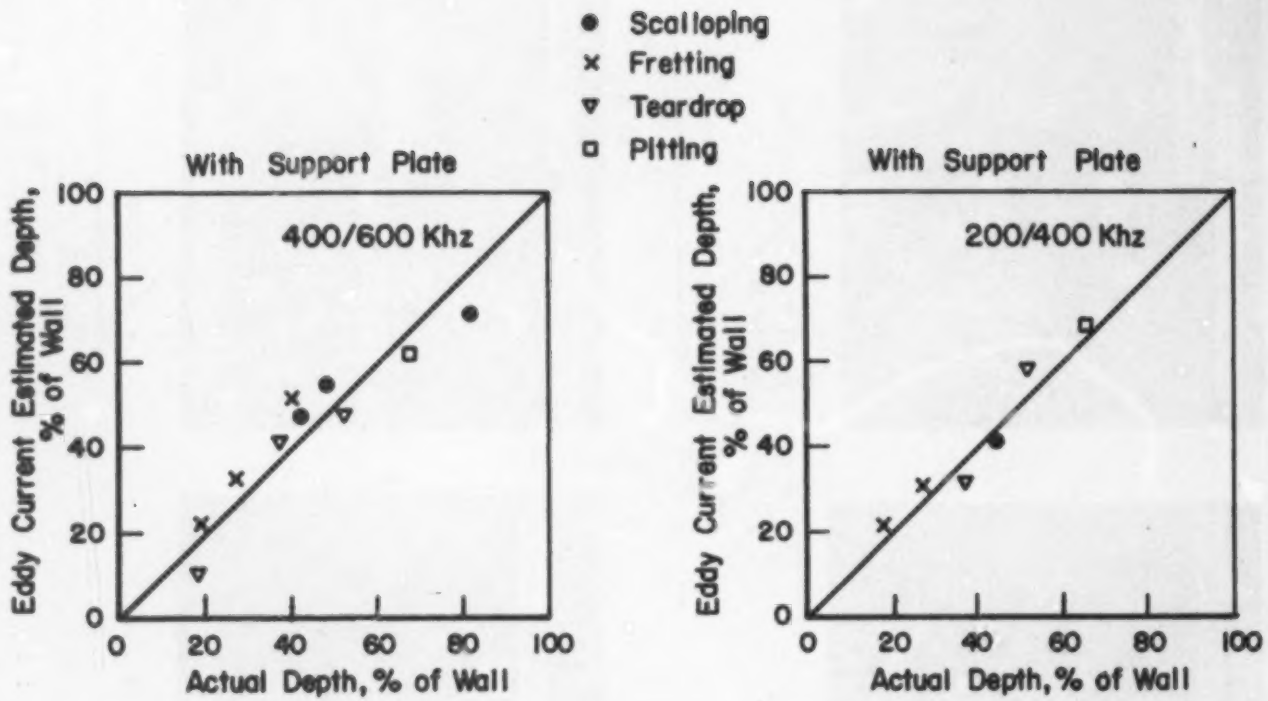


FIGURE 50. SCATTER PLOT OF ACTUAL DEPTH VERSUS EDDY CURRENT ESTIMATED DEPTH FOR OTSG DEFECT TYPES

using either mix as the scatter plots illustrate. The only exception was in the characterization of a shallow, i.e., 19 percent depth, teardrop defect. The 200/400 KHz signal was rotated significantly such that its depth would have been grossly underestimated. The 400/600 KHz combination did not underestimate as much.

DISCUSSIONS AND CONCLUSIONS

The support plate mixing errors shown in Figures 31 and 38 were derived using signal amplitudes approximating defect standards in use by the RSG and OTSG in-service inspection community. The scatter in the data is the result of defect position dependent phenomena within the support plate. For defect signals of lessor or greater amplitudes, the uncertainty or scatter in the data will increase or decrease accordingly. As an example, using data derived from the 400/600 KHz 0.040" wall tube frequency combination, Figure 51 illustrates the depth percentage position dependent uncertainty which can exist for a hole of 40 percent depth as a function of the normalized input signal-to-noise ratio. The input signal-to-noise ratio ζ is defined to be the ratio of the magnitude of the defect signal amplitude to plate signal magnitude measured at the basic frequency. As the initial signal amplitude gets larger, the signal-to-noise ratio increases and the uncertainty in providing a reliable depth estimate decreases accordingly. Extrapolation of the curve in Figure 51 suggests that for an input signal-to-noise ratio on the order of 1.1, the mixing error uncertainty approaches zero. This can be seen from Figure 37, where the defect signal phase angle for the largest series of holes is essentially constant independent of where the holes are located within the support. The ratio ζ at which the defect position dependent mixing error becomes tolerable is a function of the frequencies F3 and F2 used to suppress the plate and for the combinations considered varies as shown in Table 2(a). For defect models considered in this program the ζ values assumed by the particular types at depths on the order of the plugging limit are shown in Table 2(b). From a practical standpoint, the wastage type defect is the only one which occurs with any regularity associated with the tube sheet or support plate in RSG's, although a few plants have had recent occurrences of stress

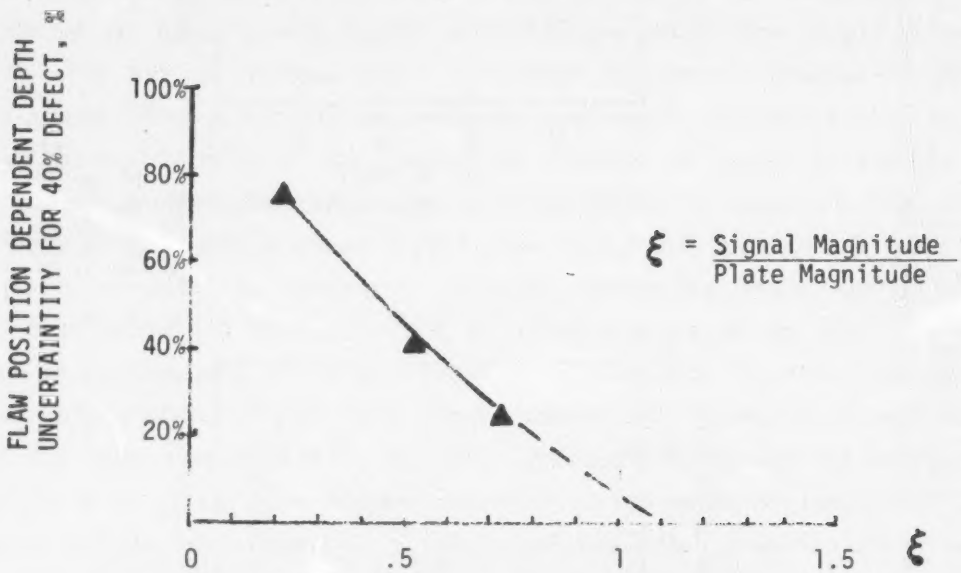


FIGURE 51. POSITION DEPENDENT FLAW DEPTH UNCERTAINTITY FOR A 40% THROUGH WALL DEFECT VERSUS RATIO OF SIGNAL MAGNITUDE TO PLATE MAGNITUDE.

TABLE 2. BASIS FREQUENCY INPUT SIGNAL-TO-NOISE RATIOS REQUIREMENTS AND VALUES ASSUMED BY TYPICAL STEAM GENERATOR DEFECT TYPES

	F3/F2	ζ *
0.040" Tube		
	400/600 KHz	1.1
	200/400 KHz	1.3
0.050" Tube	100/400 KHz	2
	200/400 KHz	.8

(a)

Defect Type	ζ
Wastage	>>1
Cracks	<1
Pitting	<<1
Fretting	>>1
Teardrop	>1
Scalloping	>>1

(b)

* Lower ζ values indicate better plate repression capability

corrosion cracking in the tube sheet crevice region. Cracking in proximity to the tube sheet or support plate has been observed in OTSG's (high-cycle fatigue crack). These have generally all been leakers which result in much larger ζ values shown in Table 2. Hence, their characterization is more reliable. Pitting is the most problematical defect to accurately characterize because of its small ζ value. From a safety standpoint this is of little concern although it may represent a plant availability problem, i.e., shutdown for minor tube leaks.

The 400 KHz is a common basis frequency in use for steam generator tubing inspection. When combined with appropriate plate mixing frequencies, desired phase spread or plate residuals can be achieved. Good dent suppression can also be achieved, however, existing multiparameter instrumentation would be improved by the addition of amplification/filtering to boost the magnetic tape recorder input signal-to-noise ratio. This is due to the large input levels of typical dent signals with the imposed constraint of reducing multiparameter instrumentation gain to avoid saturation.

Multiparameter eddy current can characterize defects in the presence of extraneous variables. Limitations in the overall characterization accuracy are related to the particular defect type and the choice of reference standard used to establish the phase angle versus depth calibration curve. Appropriate defect models should be used in estimating multiparameter mixing error to develop confidence limits for eddy current data generated during in-service inspection outages.

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